Causes and Impacts of Class One Engineering Changes: An Exploratory Study Based on Three Defense Aircraft Acquisition Programs

by

Teng-Cheng Hsu

Bachelor of Science, Aerospace Engineering
University of Maryland, College Park, 1996

Submitted to the Department of Aeronautics and Astronautics
and the
Technology and Policy Program in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Aeronautics and Astronautics

and

Master of Science in Technology and Policy

at the
Massachusetts Institute of Technology
June 1999

Signature of Author____________________________
Department of Aeronautics and Astronautics, and Technology and Policy Program
May 21, 1999

Certified by_____________________________________
Kirkor Bozdogan
Principal Research Associate, Center for Technology, Policy, and Industrial Development
Thesis Supervisor

Certified by_____________________________________
John J. Deyst, Jr.
Professor, Department of Aeronautics and Astronautics
Thesis Supervisor

Accepted by_________
Richard de Neufville
Chairman, Technology and Policy Program

Accepted by_____________________________________
Jaime Peraire
Chairman, Department of Aeronautics and Astronautics Graduate Committee

This page is intentionally left blank.

Causes and Impacts of Class One Engineering Changes: An Exploratory Study Based on Three Defense Aircraft Acquisition Programs

by

Teng-Cheng Hsu

Submitted to the Department of Aeronautics and Astronautics and the
Technology and Policy Program on May 21, 1999 in Partial Fulfillment of the Requirements for
the Degrees of Master of Science in Aeronautics and Astronautics and Master of Science in
Technology and Policy

Abstract

Past studies on engineering changes have focused on products other than defense aerospace products, and have concentrated primarily on the design-manufacturing interface within single companies. Thus, engineering changes in the context of US defense aerospace product development - where the user community, the acquisition community, and the contractors share the responsibility for developing a product - remain largely unexplored.

This research focused on three defense aircraft acquisition program case studies, referred to hereafter as Programs A, B, and C. The primary goal of these studies was to develop a better understanding of the causes and impacts of Class I engineering changes in the US defense aerospace product development context. Class I engineering changes, simply referred to as engineering changes below, are those that fundamentally modify the form, fit, and/or function of a product such that the results before and after the engineering changes are different, and are visible to all communities involved with developing the product. In addition, this research sought to identify ways in which contractors and customers may help to reduce the number of undesirable engineering changes.

For the three case-study programs, requirements definition issues, changes in user needs, the need to fix deficiencies, and technological changes were found to be the four dominant causes of engineering changes. It was also found that program characteristics determined the dominant causes in each of the programs. Engineering changes due to the four dominant causes across the three case-study programs were found to be most likely of high-impact. The scope of impact of engineering changes remained relatively constant with respect to time, and engineering changes rarely led to subsequent, unanticipated engineering changes. Thorough requirements definition facilitated by the use of integrated product teams (IPTs), prioritization on program schedule, and the use of mature technologies combined to allow Program C to make frequent engineering changes to accommodate evolving user needs and changes in technology without any program schedule delay. It was also found that had IPTs been used during the development phases of Programs A and B, the prime contractors and their suppliers might have been able to avoid some engineering changes.

Thesis Supervisors:

Dr. Kirkor Bozdogan
Title: Principal Research Associate, Center for Technology, Policy, and Industrial Development
Professor John Jacob Deyst, Jr.
Title: Professor of Aeronautics and Astronautics

Acknowledgements

I would like to thank the people and organizations that made my research and thesis possible. First, my gratitude goes to the Lean Aerospace Initiative and MIT for supporting me, and providing me with the unique opportunity to study a topic that I would not have otherwise chosen had I joined another research group or attended another school. Second, I would like to thank the Department of Aeronautics and Astronautics for providing a challenging and rewarding learning environment.

My advisors, Dr. Bozdogan and Professor Deyst, gave me their time, wisdom, and patience. Thank you very much for being there at the times of crisis and major steps forward, in terms of both my research and professional development.

To the present and former Research Assistants, Staff, and Researchers I came in contact with while at LAI, thank you very much for exchanging ideas with me, and for coming to my rescue. Special thanks to Matt, David, Mario, and Aimee for making the darkest hours of research seem almost like fun with your friendship, support, and sense of humor. Special thanks to Dr. Rebentisch for your encouragement and help.

Special thanks to Ross and Stacy for helping me start my research at all. You brought me over the hurdle of feeling very helpless and hopeless.

My heartfelt thanks also go to everyone I have ever interacted with at the SPO, the program offices, and the contractor locations who responded to my endless questions and requests for assistance with utmost generosity, expertise, and professionalism. Especially, thank you to the configuration managers at the SPO for being so patient while helping me with my research on a daily basis.

My graduate education would not have been possible without the support and love of my family and friends. Thank you Mom, Dad, Wei-Teene, Uncle, and Grandma for letting me grow and learn. To all my friends I grew up with all the way through graduate school, thank you, and I enjoy and value every minute of hanging out with you.

Last but not least, my most grateful thanks to Alice for being there with me every minute through times of anger, crisis, hope, and happiness. There can never be enough said for what you have done to help me.

Author's Contact Information

tedhsu@alum.mit.edu

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction and Overview

1.1 Problem Overview

The primary purpose of this research is to develop guidelines for reducing defense aerospace product development cycle time and cost. The research documented in this thesis builds on the earlier work of Hernandez[1]. Based on empirical data from a total of three commercial and defense aircraft program case studies, Hernandez found that while a combination of common databases with 3D capability, multi-functional teams, and concurrent engineering have contributed to reductions in the number of rework cycles, measured as the number of engineering changes per initial design drawing release[2], it was not clear whether there was a driver among the three factors[3]. The follow-up study of Hernandez's earlier work was originally meant to discern which of the factors - common databases with 3D capability, multi-functional teams, and concurrent engineering - may have contributed to the reduction in the number of rework cycles, or engineering changes.

The literature review conducted as a part of the research reported here led to two conclusions. First, other than the work of Hernandez, the majority of past studies of engineering changes have not focused on the US defense aerospace product development environment. Second, most of these studies have concentrated on the design-manufacturing interface.

An important implication of these two conclusions is that engineering changes reflective of the characteristics of the US defense acquisition and aerospace product development environment remain largely unexplored. A simplified view of the US defense acquisition and aerospace product development environment is shown in Figure 1-1 to represent the sharing of responsibilities over a defense product development program by the user community ("Operation"), the acquisition community ("Advisory Committee"), and the contractors

---

[1] Hernandez, Christopher M. *Challenges and Benefits to the Implementation of Integrated Product Teams on Large Military Procurements*. MIT Master of Science in Management Thesis, June 1995.
[2] Hernandez: 1995, p.36.
[3] Hernandez: 1995, p.110.

("System Management")[4]. Much of the previous efforts that studied engineering changes, by concentrating on the design-manufacturing interface, largely ignored the many other interfaces that characterize the defense aerospace product development environment.

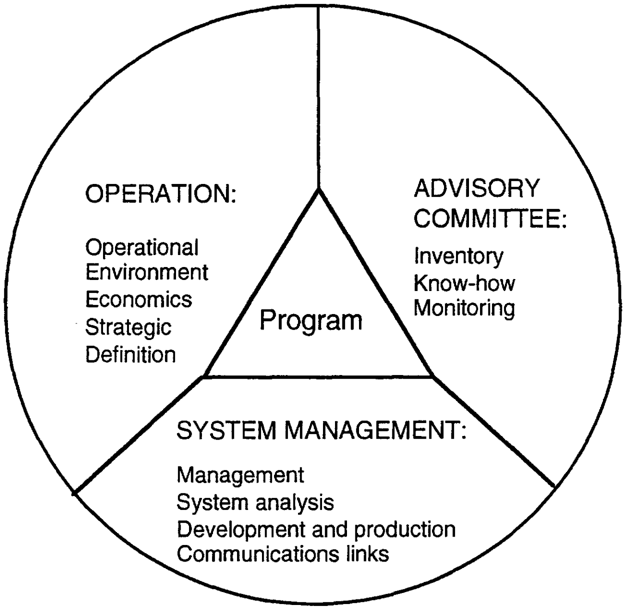


Figure 1-1: Simplified view of the US defense acquisition environment

Class I engineering changes[5] are those that fundamentally modify the form, fit, and/or function of the product in such a way that the functionalities or physical configuration of the product are different before and after the change. They represent an important element of the defense aerospace product development environment and process in terms of cycle time and cost in product development. Because of these characteristics, a Class I engineering change made to a defense product is visible to all the communities involved in developing that product, and it is reviewed and processed by these communities for approximately 90 days[6].

As implied in the preceding discussion, there are at least two approaches to studying the relationship between engineering changes and defense aerospace product development cycle time

---

[4] The figure and the discussion are based on Ellis, David O. and Fred Ludwig. *Systems Philosophy*. Englewood Cliffs, NJ: Prentice-Hall, Inc. 1962, p.93, and from Blanchard, Benjamin S. *System Engineering Management*. New York, NY: John Wiley & Sons, Inc. 1991, pp.251-253.

[5] For US defense acquisition, Class I engineering changes have been governed by *MIL-STD-480B Configuration Control - Engineering Changes, Deviations and Waivers*. 15 July 1988. MIL-STD-480B has been superseded by MIL-STD-973.

and cost. The first approach is to focus on the design-manufacturing interface within single organizations. This approach has been frequently used in the past as already indicated. The second approach is to understand the fundamental realities characterizing the defense acquisition and aerospace product development environment, and the relationships between this environment and Class I engineering changes. The latter approach focuses on a higher level set of issues and questions than those involved in the design-manufacturing interface. The research pursued in this thesis follows the second approach. This allows for a modification of the follow-up study of Hernandez's earlier work by taking a step back to gain a fundamental understanding of engineering changes that are visible to multiple communities in the defense acquisition and aerospace product development context.

1.2 Research Objectives

This research was conducted with two objectives in mind. One objective was to contribute knowledge to the area of engineering changes by concentrating on the fundamental nature - causes and impacts - of Class I engineering changes in the context of US defense aerospace product development. The second objective was to develop guidelines for reducing defense aerospace product development cycle time and cost.

1.3 Key Questions

Several key questions were addressed, with the goal of achieving the research objectives. These questions are:

- What are the causes and impacts of Class I engineering changes?
- What are specific product development practices that would help reduce the number of undesirable engineering changes?
- What can the acquisition customer organizations do to reduce the number of undesirable engineering changes?

---

[6] Based on data a Defense Contracts Management Command (DCMC) representative showed to the researcher during a 14 April 1998 site visit to a prime contractor's facility.

For the remainder of the thesis, unless explicitly stated otherwise, the term "engineering change" refers to a Class I engineering change.

1.4 Research Design: An Overview

The research documented in this thesis is based on case studies focusing on three major USAF aircraft programs in the electronics sector. All three programs, designated as Programs A, B, and C for the purposes of this thesis, are the responsibility of a single System Program Office (SPO). Data on 118 engineering changes[7] were collected from contractor-submitted Class I Engineering Change Proposals (ECPs) archived at the SPO. In addition, supporting documents pertaining to the three programs, as well as to the specific systems and subsystems within each of the three programs, were collected in order to assist in developing a comprehensive understanding of these engineering changes. Finally, 54 engineers and managers from prime contractors and the program offices were interviewed to obtain their perspectives on the programs and the engineering changes. The causes and impacts of specific engineering changes were determined through a detailed examination of the data from these sources. Finally, broader interpretations and conclusions were drawn from the collected database.

1.5 Highlights of Research Findings

The key findings based on Programs A, B, and C are highlighted here. They pertain to the causes and impacts of Class I engineering changes, and the roles of the contractors and the customer in reducing defense aerospace product development cycle time and cost.

Two key findings pertaining to the causes of engineering changes on the three case-study programs are highlighted here. The four dominant causes of engineering changes *across the three programs* were found to be the design assumptions made in the initial phases of the programs, evolution of user needs as programs progressed over time, the need to correct design/product deficiencies, and changes in technology. However, the combinations of dominant causes were

---

[7] This number, 118, includes two engineering changes that applied to more than one program.

different *from program to program*, and were strongly dependent on the characteristics of the individual programs.

Some examples of findings pertaining to the impacts of engineering changes on the case-study programs are highlighted below. These findings were determined based on seven areas, or ways, in which the program and communities, depicted in Figure 1-1, could be affected by engineering changes. For example, it was found that engineering changes almost always increase the near-term cost of the programs. It was also found that engineering changes seldom led to additional, unanticipated, engineering changes. Furthermore, in terms of product performance, it was found that engineering changes most often resulted in meeting performance expectations - either by meeting shifted expectations or by meeting originally specified expectations.

The pair-wise relationships between causes and impacts of engineering changes in the three case-study programs, and time, in terms of when during a program an engineering change was made, were also explored. It was found that the engineering changes due to the four dominant causes identified above were most likely to be of high-impact - at least four out of seven areas were affected by such engineering changes. Furthermore, the mean (average) number of areas impacted by engineering changes in the three case-study programs remained relatively constant over time. Finally, no particular relationship between the causes of engineering changes and time was found across the three case-study programs.

This research also identified some lessons learned about the possibility of reducing undesirable engineering changes and undesirable impacts of engineering changes. The prime contractor's use of integrated product teams (IPTs), for development-related activities, were found to help reduce the proportion of engineering changes that were due primarily to requirements definition. Furthermore, in Program C, it was found that by properly defining requirements early in the program, it was possible to quickly respond to changes in user needs and technology and accommodate them by making engineering changes. Several factors may have enabled Program C to make these engineering changes without program schedule delay. These include recognition of program schedule as a priority, the ability to properly define major requirements early in the program, and the use of mature technologies.

Some experiences of Programs A and B illustrated the importance of having prime contractors understand the capabilities and limitations of their key suppliers. Despite the fact that key suppliers were involved early on in these two programs, some design requirements were not well understood among the parties, and redesigns became necessary later. Some redesigns were sufficiently serious that they severely impacted the suppliers. The use of IPTs on these two programs might have enabled the prime contractors to have greater understanding of their key suppliers' capabilities and clarify some of the key requirements early in the programs, thereby avoiding some engineering changes that severely impacted the key suppliers.

The customer also had a role to play in reducing undesirable engineering changes and undesirable impacts of engineering changes. The Program B case study showed that having two associate contractors - essentially two prime contractors - during the development phase, with the customer as integrator, increased the risk of information disconnect between the two contractors who must cooperate to develop the product. In addition this dual-prime arrangement sometimes required two engineering changes to deal with one issue. The Program C case study also showed that the use mature technology, when feasible, helped enable frequent engineering changes to achieve incremental product improvement with no program schedule delay.

1.6 Thesis Outline

This section outlines the remainder of the thesis by identifying the main thrusts of each subsequent chapter. Chapter 2 establishes the theoretical basis for the research. It highlights the review of some engineering change-related publications, discusses the foundation of the research in systems engineering, compares the characteristics of Class I and Class II engineering changes in the context of defense product development, and reviews frameworks by which causes and impacts of engineering changes have been studied in the past. Chapter 3 describes the research method, the database collected for this research, and data analysis frameworks and procedures employed in this research. Chapter 4 describes the characteristics of the three case-study programs, and relates the causes of engineering changes in these programs to program characteristics. Chapter 5 focuses on the impacts of engineering changes. Based on the data presented in Chapters 4 and 5, Chapter 6 explores the pair-wise relationships between causes of engineering changes, impacts of engineering changes, and time. Finally, Chapter 7 concludes the thesis by reviewing the research process and the findings, discussing the limitations of the research, and recommending directions for future work.

This page is intentionally left blank.

2. Background and Overview of Previous Work

This chapter establishes the theoretical background of the research. Section 2.1 first explains, in a problem statement format, the motivation for the research. Section 2.2 provides an overview of previous work in the area of engineering changes in order to identify gaps in knowledge. Section 2.3 introduces several systems engineering concepts and practices that guided the research, and Section 2.4 identifies the particular class of engineering changes studied in the research. Finally, Sections 2.5 and 2.6 examine the specific ways in which causes and impacts of engineering changes have been previously studied.

2.1 Problem Statement

While engineering changes have been identified as factors impacting product development in various industries, very few studies have addressed engineering changes in the context of US defense aerospace product development. In order to contribute to the knowledge base in this area, the research documented in this thesis concentrates on the causes and impacts of engineering changes that are reflective of US defense aerospace product developments. The research also attempts to develop guidelines for reducing product development cycle time and cost in this context.

2.2 Overview of Engineering Change-Related Work

This section highlights results of the literature review that provided the primary direction for this research. These results are discussed in terms of research setting, and product development interfaces studied. Details of eight particularly relevant publications in the area of engineering changes are summarized in Appendix A.

2.2.1 Highlights of Literature Review

Research Setting

From a sample of available engineering change-related publications, it is interesting to note that little work have been done in the US defense aerospace product development environment.

While a subset of these studies[8] examined engineering changes in various industries including aerospace, they did not focus specifically on the defense aerospace industry. Consequently, it may be difficult to extract lessons learned about engineering changes from such broadly-set studies. On the other hand, some narrowly-focused studies concentrated on commercial products, such as automobiles and photocopiers[9], that did not directly pertain to the defense aerospace product development environment. As a result, it may still be difficult to extrapolate lessons learned about engineering changes to the defense aerospace product development environment. Furthermore, the only study performed on the aerospace industry focused on the commercial aircraft sector[10]. Since the problems facing the commercial aircraft sector may be significantly different from those facing the defense aerospace sector, it may not be valid to extend lessons learned from such a study to the defense aerospace sector.

Product Development Interfaces Studied

A review of the eight publications that focused on engineering changes also indicated that much of the previous work has addressed engineering changes in terms of the design-manufacturing interface. This was evident in Hegde et al.[11], Ettlie[12], Coughlan[13], Hooper[14], and

---

[8] An example is such studies was Ettlie, John E. "Early Manufacturing Involvement in New Product Development". *Proceedings of the Institute of Electrical and Electronics Engineers (IEEE) Engineering Management Conference*, 1995, pp.104-109. Another example was Fricke, Ernst, Bernd Gebhard, et al. "No Innovation without Changes, but..." *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. pp.601-608. According to an in-person conversation with Fricke conducted at the Massachusetts Institute of Technology, 17 July 1998, this research was based on interviews conducted at 20 German companies across a number of industries, including aerospace.

[9] Barkan, Philip. "Productivity in the Process of Product Development - An Engineering Perspective". *Integrating Design and Manufacturing for Competitive Advantage*, Gerald Susman, Ed. New York, NY: Oxford University Press, 1992, pp.56-68.

[10] Hooper, Eric Allen. *Improving the Boeing 777 Program's Corrective Action Process*. MIT Master of Science in Electrical Engineering and Master of Science in Management Thesis. May 1996.

[11] Hegde, G. G., Sham Kekre, and Sunder Kekre. "Engineering changes and time delays: A field investigation". *International Journal of Production Economics, Vol. 28*, Elsevier Science Publishers B.V., 1992. pp.341-352.

[12] Ettlie, John E. "Early Manufacturing Involvement in New Product Development". *Proceeding of the IEEE Engineering Management Conference*, 1995. pp.104-109.

[13] Coughlan, Paul D. "Engineering Change and Manufacturing Engineering Deployment in New Product Development". *Integrating Design and Manufacturing for Competitive Advantage*, Gerald Susman, Ed. New York, NY: Oxford University Press, 1992.

[14] Same as Footnote 10.

Wright[15]. Indeed, Wright indirectly observed the predominance of the design-manufacturing interface in engineering change-related studies based a close examination of 23 engineering change-related papers[16]. However, as shown in Figure 1-1, there are more possible interfaces among the communities involved in defense aerospace product development than just the design-manufacturing interface. Therefore, engineering change-related lessons learned in the aforementioned studies may not be directly transferable to defense aerospace product development.

2.2.2 Direction of Research

The gaps in knowledge identified above by the literature review suggested the direction of the research reported here. The goal was to contribute new knowledge to the area of engineering changes by concentrating specifically on engineering changes in the US defense aerospace product development environment. In addition, since this environment can be characterized by the sharing of product development responsibilities across the user community, acquisition community, and the contractors as shown in Figure 1-1, the research may make a further contribution by also examining the relationship between engineering changes and the interactions among these communities.

2.3 Systems Engineering Concepts and Practices

Having identified the direction of research, it is useful to understand some concepts and practices that relate to engineering changes in the defense aerospace product development context. These concepts and practices include: systems, complexity, changes, systems engineering, and configuration management. The following discussion explains the relevant concepts and practices. Readers interested in more details can refer to the cited references.

---

[15] Wright, I. C. "A review of research into engineering change management: implications for product design". *Design Studies, Vol. 18*, 1997. pp.33-42.
[16] Wright: 1997, p.37 and p.41.

2.3.1 Relevant Concepts: System, Complexity, and Changes

It has been noted, at least since the 1950s[17] and 1960s[18], that the weapon systems acquired by the military services have become increasingly complex. It has also been predicted[19] that the complexity of weapon systems will increase to a point where no one company or military service would have all the expertise to design, produce, and support a complete system. Thus, the responsibilities of designing, producing, and supporting a system would become increasingly shared by the user community, the acquisition community, the prime contractor, and subcontractors[20].

In order to better understand the concepts of system and complexity, they need to be further explored. Ellis and Ludwig considered a *system* to be any device, procedure, or scheme which follows certain rules to convert inputs to outputs, both of which may take the form of information or materials[21]. A system has also been considered as a collection of interrelated elements whose functionality is greater than the sum of the independent element functionalities[22]. Just as a system can be broken down to its elements, a system can also be an element of a larger system[23]. The interactions among the interrelated elements, which may include "things" and "people", of the devices, procedures, and schemes then characterize *complexity*[24].

Changes are related to the concepts of system and complexity because in a complex system a change to an element affects many other elements in a typically nonlinear fashion[25]. Goode and Machol underscored the relationship between changes and complex systems by asserting that a complex system is understood only if the nonlinear effects of changes on such a

---

[17] As in, for example, Goode, Harry H. & Robert E. Machol. *System Engineering: An Introduction to the Design of Large-Scale Systems*. New York, NY: McGraw-Hill Book Company, Inc. 1957.

[18] As in, for example, Ellis, David, O. & Fred J. Ludwig. *Systems Philosophy*. Englewood Cliffs, NJ: Prentice-Hall, Inc. 1962.

[19] The prediction was made by Ellis & Ludwig: 1962, p.92.

[20] The sharing of responsibilities by the different communities is based on Ellis & Ludwig: 1962, p.92. The specific mention of subcontractors is based on Blanchard, Benjamin S. *System Engineering Management*. New York, NY: John Wiley & Sons, Inc., 1991, pp.252-253.

[21] Ellis & Ludwig: 1962, p.3.

[22] Boppe, Charles W. "Systems Engineering Elements Addressing Complexity". MIT 16.870 Aerospace Product Design lecture notes. Fall 1996.

[23] Same as Footnote 22.

[24] Based on discussion in Flood, Robert L & Ewart R. Carson. *Dealing with Complexity: An Introduction to the Theory and Application of Systems Science*, 2nd ed. New York, NY: Plenum Press, 1993, pp.24-25.

system are understood[26]. Therefore, these authors highlighted the value of studying the effects, or impacts, of changes on systems in order to understand the complexity of systems.

The concepts of system, complexity, changes, and their relationship make it possible to consider the defense aerospace product development process as a system whose elements - the user community, the acquisition community, the prime contractor, and subcontractors - interact with and affect each other. These elements and their interactions in turn affect the product they are jointly developing. Consequently, it is also possible to extend Goode and Machol's assertion to include understanding the causes of changes as a way to understand defense aerospace product development complexity. Therefore, the research documented in this thesis studies both the causes and impacts of changes, or more specifically, causes and impacts of engineering changes in the defense aerospace product development environment.

2.3.2 Relevant Practices: Systems Engineering and Configuration Management

Systems engineering is an approach to dealing with the complexity of products and processes. It is a top-down, iterative process of applying scientific and engineering knowledge to transform customer needs into a physical product that satisfies the customer needs[27]. Within systems engineering, configuration management is a function that helps to ensure that as the design undergoes the iterative process, the eventual product will fulfill the needs defined at the beginning of the process.

One of the configuration management processes that is of particular interest to this research is configuration control. It is a process for understanding, controlling, and monitoring the changes which affect the configuration or documentation of a product[28]. A very important consequence of this definition is that an engineering change (or simply, a change) to a product can include either or both a change to the product itself, and the documents describing the product.

---

[25] Goode & Machol: 1957, pp.5-6.
[26] Goode & Machol: 1957, p.6.
[27] Blanchard: 1993, pp.12-13.
[28] Monahan, Ray E. *Engineering Documentation Control Practices and Procedures*. New York, NY: Marcel-Dekker, Inc., 1995, p.57.

Engineering changes in the defense aerospace product development context are subjects of the next section.

2.4 Engineering Changes in Defense Product Development

This section introduces engineering changes within the context of US defense aerospace product development. Engineering changes in this context fall into the domain of configuration control. Figure 2-1 attempts to illustrate the organization of systems engineering and the hierarchy into which configuration control and engineering changes fit.

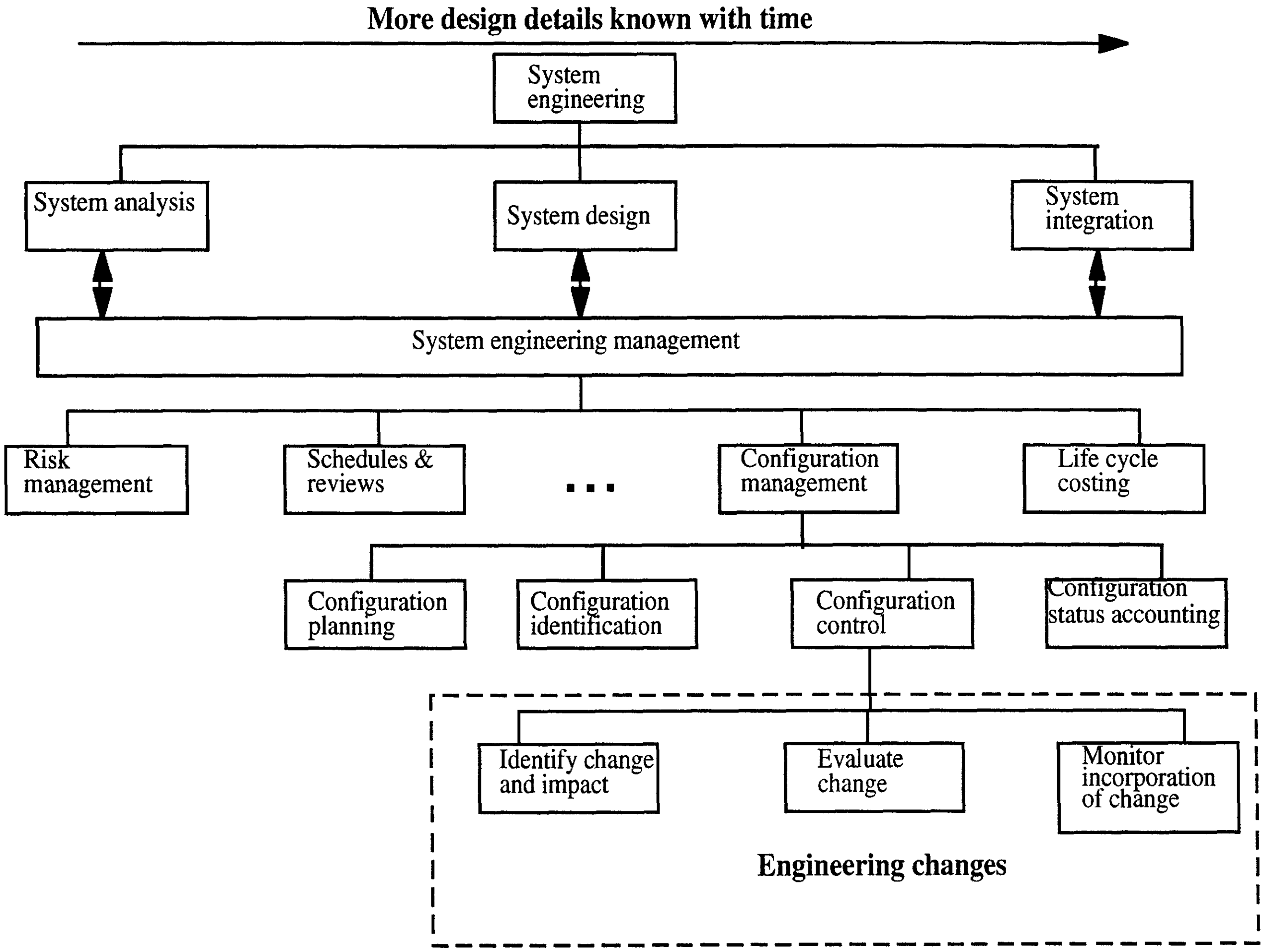


Figure 2-1: Engineering changes and systems engineering[29]

---

[29] The figure is based on a similar figure in Boppe, Charles W. "Systems Engineering And Complexity". MIT 16.880 Systems Engineering lecture notes. 1997. Elements in the hierarchy below "Configuration Management" are taken from Monahan, and Samaras, Thomas T. & Frank L. Czerwinski. *Fundamentals of Configuration Management*. New York, NY: Wiley Interscience, 1971.

Based on MIL-STD-480B, an engineering change in defense product development may be more precisely defined as "[a]n alteration in the approved configuration identification of a CI [configuration item] under development, delivered, or to be delivered."[30] A configuration identification is the set of documents, such as specifications, drawings, numbering systems, and other references that describe the configuration item in terms of its functional and physical characteristics[31]. A configuration item is a design or a physical product, consisting of either or both hardware and software, that performs a set of functions required by the customer[32].

The preceding discussion of engineering changes in the defense product development context can be summarized in terms of two main ideas. First, a change to a design should be thought of as both a modification that can be made to the physical manifestation of an idea, and a modification to the rules (requirements, specifications) describing what functions that physical manifestation must perform. Second, an engineering change can be made to a system or its subsystems at any point during development, production, and operation phases, as the basic definition indicated above.

2.4.1 Class I vs. Class II Engineering Changes

In MIL-STD-480B engineering changes are distinguished as Class I and Class II engineering changes. This section discusses the distinction.

A Class I engineering change is one that affects a configuration item or its components[33] in such a way as to (a) correct deficiencies; (b) add or modify interface or interoperability requirements; (c) make a significant effectiveness change in operational or logistics support requirements; (d) achieve substantial life-cycle costs/savings; or (e) prevent slippage in an approved production schedule[34]. These engineering changes address the modifications that have life cycle implications to the form, fit or function of a system or its subsystems. Furthermore,

---

[30] *Military Standard 480B (MIL-STD-480B) Configuration Control - Engineering Changes, Deviation, and Waivers*. 15 July 1988. Section 3.1.30.
[31] *MIL-STD-480B,* Section 3.1.14.
[32] *MIL-STD-480B,* Section 3.1.15.
[33] *MIL-STD-480B*, Section 5.1.
[34] *MIL-STD-480B*, Section 5.1.2.

Class I engineering changes are apparent to the customer[35], and the functionality and/or physical configuration of parts, components, and subsystems are not interchangeable before and after the change[36]. For example, the user community is likely to know how operational characteristics resulting from an engineering change differed from those originally specified. Finally, if any contractual factors such as cost-to-customer, contractual guarantees/warranties, deliveries, or contract milestones are impacted, the engineering change must be a Class I[37].

A Class II engineering change has been defined as one that is a minor modification, transparent to the customer, made to a configuration item in production[38]. The substitution of parts from one company by identical parts from another company would be an example of a Class II engineering change[39]. Thus, the interchangeability of parts would be preserved before and after the change[40].

Table 2-1 summarizes the comparison between Class I and Class II engineering changes. The distinctions come from the definitions and characteristics provided in the discussion above.

	Class I	**Class II**
Form, fit, function (includes performance) change apparent to customer	Yes	No
Qualitative distinction of scope of change's impact	High	Low
Functionality and/or physical configuration interchangeable before and after change	No	Yes

Table 2-1: Summary of Class I vs. Class II engineering changes

2.4.2 Rationale for Studying Class I Engineering Changes

The characteristics of Class I engineering changes discussed above suggest their compatibility with the objectives of this research. Since Class I engineering changes are most

---

[35] This concept had also been discussed in Coughlan, Paul D. "Engineering Change and Manufacturing Engineering Deployment in New Product Development." *Integrating Design and Manufacturing for Competitive Advantage*. New York, NY: Oxford University Press. 1992.

[36] The interchangeability view of ECPs has been highlighted in Monahan, Ray E. *Engineering Documentation Control Practices and Procedures*. New York, NY: Marcel Dekker, Inc. 1995. pp.83-85.

[37] *MIL-STD-480B*, Section 5.1c.

[38] *MIL-STD-480B*, Section 5.2.

[39] *MIL-STD-480B*, Section 5.2.

often visible to the contractors and customers (including the user community and the acquisition community), they were considered to be more likely to highlight the broader reasons within the defense aerospace product development environment that rendered them necessary. Therefore, they were selected, over Class II engineering changes, as the engineering changes of interest.

2.5 Existing Frameworks for Categorizing Causes of Engineering Changes

This section reviews four existing frameworks found in the literature and in practice for categorizing causes of engineering changes. Since the previous sections have indicated the importance of studying the causes and impacts of engineering changes in defense aerospace product development, it is necessary to first understand how causes of engineering changes have been examined and quantified in the past.

Before examining the frameworks themselves, there needs to be a set of criteria for assessing the suitability of existing frameworks for use in studying causes of engineering changes in defense aerospace product development. In light of the gaps in knowledge identified at the end of Section 2.2, a framework that might be adopted for use in this research should examine various product development issues, provide a systems view of US defense aerospace product development, and extract lessons learned.

Table 2-2 shows a comparison of various frameworks in terms of the criteria stated above. The details of each framework are included in Appendix B.

---

[40] Same as Footnote 36

	Examine a Variety of Product Development Issues.	**Provide Systems View of US Defense Aerospace Product Development.**	**Extract Lessons Learned.**
Coughlan[41]	Employed for studying engineering changes pertaining to manufacturing (mfg.) and the design-mfg. interface.	Limited to the design-mfg. interface.	Limited to the design-mfg. interface, but capable of extracting lessons learned when supported with additional data.
Fricke et al.[42]	Addresses engineering changes throughout system life cycle.	Attention to both technical and organizational issues indicates that the framework does provide a systems view.	When combined with engineering change data and the product development process/practices data, the framework enables learning from existing programs.
DCMC's Categorization of Class I ECPs[43]	Addresses engineering changes throughout system life cycle.	Too high-level to reflect the decisions parties make on individual programs, and the interactions among parties on these programs.	Enables monitoring by a single agency over many programs, but it cannot provide much detail and lessons about the individual programs.
MIL-STD-480B Class I ECP Justification Codes[44]	Addresses changes throughout system life cycle.	Provides systems view of defense aerospace product development.	Enables monitoring over many ECPs, but is not explicitly linked to program characteristics.

Table 2-2: Comparison of existing frameworks for categorizing causes of engineering changes

The review of existing frameworks for categorizing causes of engineering changes leads to an important observation. Each framework appeared to have been tailored for its purpose, and

---

[41] Coughlan, Paul D. "Engineering Change and Manufacturing Engineering Deployment in New Product Development" *Integrating Design and Manufacturing for Competitive Advantage.* Gerald Susman, Ed. New York, NY: Oxford University Press, 1992. pp.165.

[42] Fricke, Ernst, Bernd Gebhard, et al. "No Innovation without Changes, but..." *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. pp.601-608.

[43] Details referred to here can be found in *DCMC Metrics Guide Book, Fourth ed.* Ft. Belvoir, VA. Downloadable from World Wide Web as PDF file from http://www.dcmc.hq.dla.mil and follow the hot link "Metrics under the column "Regulations & Manuals".

[44] *MIL-STD-480B Configuration Control - Engineering Changes, Deviations and Waivers.* 15 July 1988. The newer MIL-STD-973 is similar to, and superseded 480B, but no copy of 973 was available. Section 5.1.3 of 480B defines each justification code.

appeared suitable for what it has been designed to do. Unfortunately, none of these purposes exactly coincided with the objectives of this research. Therefore, none of these existing frameworks are directly applicable to the research documented in this thesis. Consequently, it is necessary to construct a new framework suitable for the objectives of this research, based on components found in existing frameworks. This task will be performed in Chapter 3.

2.6 Existing Frameworks for Categorizing Impacts of Engineering Changes

A review of relevant literature and practices identified several domains, or areas, that have been commonly recognized as having the potential to be affected (or impacted) by engineering changes. This section discusses these domains, and now they will serve as bases for constructing a framework for categorizing impacts of engineering changes for the research reported here.

Cost[45] and schedule[46] have been frequently mentioned as domains, or areas, that can be impacted by engineering changes. For example, Fricke et al. have pointed out that while engineering changes may increase cost and delay schedule, they can also reduce cost and advance schedule[47]. In addition, Coughlan pointed out the issue of hidden costs related to scrap accounts, purchase price variances, field service accounts, etc.[48]. These issues may become more complicated when multiple organizations are involved, as in the case of the US defense aerospace product development environment.

The product itself is another domain that can be impacted by engineering changes. For example, Fricke et al.[49] state that the quality of the product might be enhanced as a result of an engineering change.

Other possible impacts of engineering changes have also been identified in both the literature and in practice. For example, subsequent engineering changes resulting from earlier engineering changes have been identified as a possible impact. Goode & Machol, and Coughlan

---

[45] For example, cost was specifically tied to return on investment in Ettlie: 1995, p.107. It was also identified as an impact of engineering changes in Fricke et al.: 1997, p.602, Coughlan: 1992, p.159.

[46] For example, schedule was specifically treated in Hegde et al.: 1992, p.342 as manufacturing time. It was also identified as an impact of engineering changes in Fricke et al.: 1997, p.602.

[47] Fricke et al. : 1997, p.603.

[48] Coughlan: 1992, p.159.

[49] Fricke et al. : 1997, p.603.

warned about this effect by discussing the nonlinear effects of changes[50] and "collateral changes to other features"[51], respectively.

Finally, the Engineering Change Proposal forms in current use provide perhaps the most comprehensive framework for studying the impacts of engineering changes. The US Department of Defense Form 1692 series require the ECP-preparing company to identify other contractors, specifications, cost-to-government, delivery schedule, labor hour expenditures from the user community, and other life cycle elements that may be impacted by proposed engineering changes[52].

The review of existing frameworks for categorizing impacts of engineering changes suggests that there exists a relatively mature and complete basis on which to tailor a framework suitable for the research documented in this thesis. The impact domains range from the simple cost-and-schedule pair to the comprehensive set outlined in the DoD Form 1692 (formally DD Form 1692) series.

2.7 Chapter Summary

A literature survey conducted as a first step of this research indicated that the research may add insights into engineering changes in the defense aerospace product development environment. The research should concentrate on causes and impacts of engineering changes that are reflective of US defense aerospace product development, and infer guidelines for reducing product development cycle time and cost in this context. In order to understand the role of engineering changes in defense aerospace product development, this chapter then discussed the systems engineering process to which engineering changes strongly relate. Finally, it reviewed existing literature and practice for specific ways in which the causes and impacts of engineering changes have been studied in the past, with the goal of preparing for the analysis of engineering

---

[50] Goode & Machol: 1957, pp.5-6.

[51] Coughlan: 1992, p.158.

[52] For details about these fields, the readers can refer to *MIL-STD-480B Configuration Control - Engineering Changes, Deviations and Waivers*. 15 July 1988.

change data collected for this research. The description of types of data collected and methods of data analysis are subjects of the next chapter.

This page is intentionally left blank.

3. Research Design

As outlined in Chapter 1, the primary goal of this research is to develop guidelines for reducing defense aerospace product development cycle time and cost. The research seeks to achieve this goal by providing an improved understanding of the causes and impacts of engineering changes in the defense aerospace context by focusing on the following key questions:

- What are the causes and impacts of Class I engineering changes?
- What are specific product development practices that would help reduce the number of undesirable engineering changes?
- What can the acquisition customer organizations do to reduce the number of undesirable engineering changes?

This chapter describes the research strategy followed in addressing these questions. Section 3.1 presents the research methodology, and Section 3.2 provides an overview of the data collected. Next, Sections 3.3 and 3.4 discuss the frameworks for interpreting the collected engineering change data with the goal of identifying and quantifying the causes and impacts of engineering changes. Section 3.5 highlights the data analysis procedure. Section 3.6 summarizes the key points of the chapter.

3.1 Research Method

3.1.1 Data Collection Setting

The research documented in this thesis focuses on engineering changes in three defense aircraft programs, which serve as three case studies. For the purposes of this thesis, the three programs are identified simply as Programs A, B, and C.

The three programs display certain similarities. First, all three programs are managed by the same System Program Office (SPO). The SPO is responsible for a fleet of aircraft[53], and

---

[53] Some of these aircraft are in the US inventory and some are in the inventories of US allies.

serves as the interface between the user community[54] and the contractors in order to acquire[55] the products and services that the user community needs[56]. Second, all three programs have significant electronics emphasis. Third, the mission aircraft under the programs - including the airframe and the electronics mission subsystems they carry - perform similar missions. Finally, products of all three programs had already entered the production phase as of Summer 1997, when the data collection effort for this research began.

These three programs also exhibit certain differences. First, the programs differ in terms of their scope. For example, while one program (including its contractors) may be responsible for developing upgrades to one major existing electronics mission subsystem carried in the aircraft, another program (including its contractors) may be responsible for developing and building complete mission aircraft (including the aircraft and the mission subsystems) from the ground up. Both of these cases were observed among the three programs studied. Second, the programs[57] may be managed differently. For example, two of the three programs began when concurrent engineering and integrated product teams were simply not in use by either the government or contractors. Third, individual programs managed by the same SPO may have employed very different contractual terms and conditions affecting different programs. For example, two of the three case-study programs had only one prime contractor during development, while a third had two prime contractors during development. These programmatic differences may affect the causes and impacts of engineering changes on the three programs, and they may provide insights into how similar programs might be managed differently in the future.

3.1.2 Data Collection Process

The data collection process was carried out in two phases: the System Program Office (SPO) phase and the prime contractors phase. The objective, in general, was to gain as much

---

[54] In the context of the USAF, these are the people who operate and maintain the aircraft and aircraft subsystems.

[55] For military aircraft, an "acquisition program" is responsible for the aircraft's research and development, design, manufacturing and assembly, training and ground equipment, initial spares, and facility construction. See Boppe, Charles W. "Complex Product Design Process." 16.870 Aerospace Product Design lecture notes. Fall 1996.

[56] A detailed discussion about the SPO's responsibilities would take more space than is available here.

[57] Once again, the distinction between government and contractor is blurred, and they are collectively referred to as "the program".

insight as possible about engineering changes in defense aerospace product development from a diverse set of perspectives.

The System Program Office Phase

With the benefit of extensive assistance from Air Force personnel, permission to conduct on-site research had been obtained from the System Program Director's Office. Research activities focused on collecting engineering change data from Engineering Change Proposals (ECPs) archived within the programs[58]. From 15 July to 17 November 1997, ECP files were obtained from the configuration manager of each program, and the entries were transcribed onto Microsoft EXCEL and WORD files[59] set up for each program. Written notes from discussions and interviews with configuration managers, engineers, and program managers were recorded, with the participants' permission, and later transcribed into the appropriate WORD files. In addition, a separate WORD file was maintained for each program to document all notes pertaining to specific engineering changes from that program.

The on-site data collection at the SPO provided the benefit of direct exposure to some aspects of the acquisition community's role in defense aerospace product development. The accessibility, expertise, and support of the SPO personnel were of great value to the research.

The Prime Contractors Phase

It was also necessary to learn about the three case-study programs and their engineering changes from the perspectives of the contractors. Thus, between 05 February and 15 April 1998, one site visit was made to each of the three prime contractors, designated as Contractors X, Y, and Z for the purposes of this thesis, of the three case-study programs. Each site visit lasted no more than three working days. During these site visits, the data collection effort benefited

---

[58] Since the SPO had been restructured, and integrated product teams (IPTs) were formed two years earlier, the ECP files were moved to the respective IPTs that ran each program. However, the older half of Program A's ECPs were found only in the archives of the SPO IPT responsible for contracting, not in the configuration management files of the program IPT.

immensely from the expert assistance provided by the contractor engineers and managers of the three case-study programs.

The purpose of both formally and informally interviewing the key contractor personnel was to learn about the background, performance, the nature of the products, and the engineering changes from the contractor perspective, for each of the three programs. Consequently, the interviews and discussions emphasized the history of the programs, and the details of each engineering change.

The treatment of the data collected at the contractor sites was similar to that of the data collected at the SPO. A main difference, however, was that a site-visit report summarizing the findings of each visit was composed and submitted to the company's contact person for review for factual accuracy. This final step ensured the validity of information collected during these visits.

The number and distribution of government and contractor personnel on specific programs who were interviewed via face-to-face meetings are shown in Table 3-1. Additional personnel who were not specifically associated a particular program were also interviewed: 3 represented the prime contractor companies, 6 represented the SPO, and 8 represented the Defense Contract Management Command (DCMC) stationed at the contractor sites. A total of 54 people were interviewed.

	Program A	**Program B**	**Program C**
Program office	5	4	2
Prime contractor (s):	13	9	4

Table 3-1: Number and distribution of personnel interviewed in the three programs

3.2 Database Supporting the Research

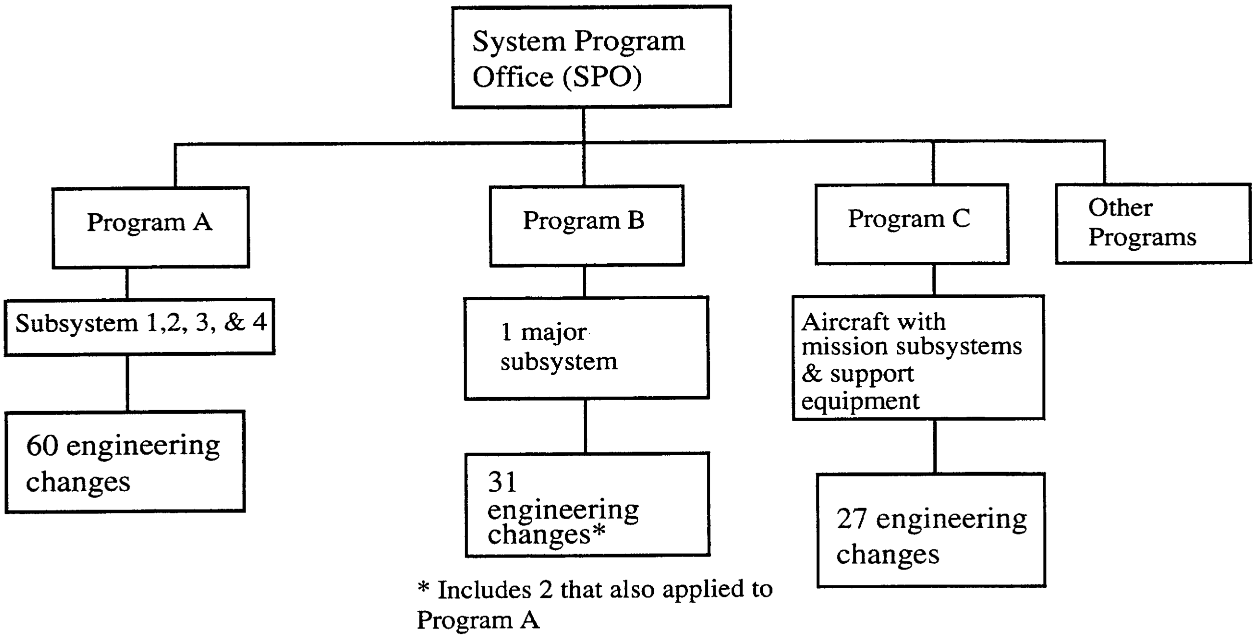
The database developed as part of this research encompassed engineering change data, and additional data about the three programs and their systems and subsystems. The data collection

---

[59] EXCEL files were suitable for recording short entries taken from DD Form 1692 series for forms (the ECP forms). WORD files complemented the EXCEL files by recording detailed descriptions, explanations, and notes from interviews and discussions.

effort was designed to provide insights into the causes and impacts of engineering changes, leading to a documentation of lessons learned about defense aerospace product development. **All data obtained were unclassified.**

The database is organized according to four levels: the SPO level, each program level, a systems and subsystems level, and an engineering change level. The four-level database structure is shown in Figure 3-1. Under each program the total number of engineering changes, as designated in Figure 3-1, includes all engineering changes approved or in review[60] by the SPO as of 17 November 1997.



* Includes 2 that also applied to Program A

Figure 3-1: Database structure

3.2.1 Engineering Change Data

Contractor-submitted Engineering Change Proposals (ECPs) provided data on 118 engineering changes across the three programs. A breakdown of the engineering change data collected is shown in Figure 3-2.

---

[60] The engineering changes that were pending approval as of 17 November 1997 were later approved.

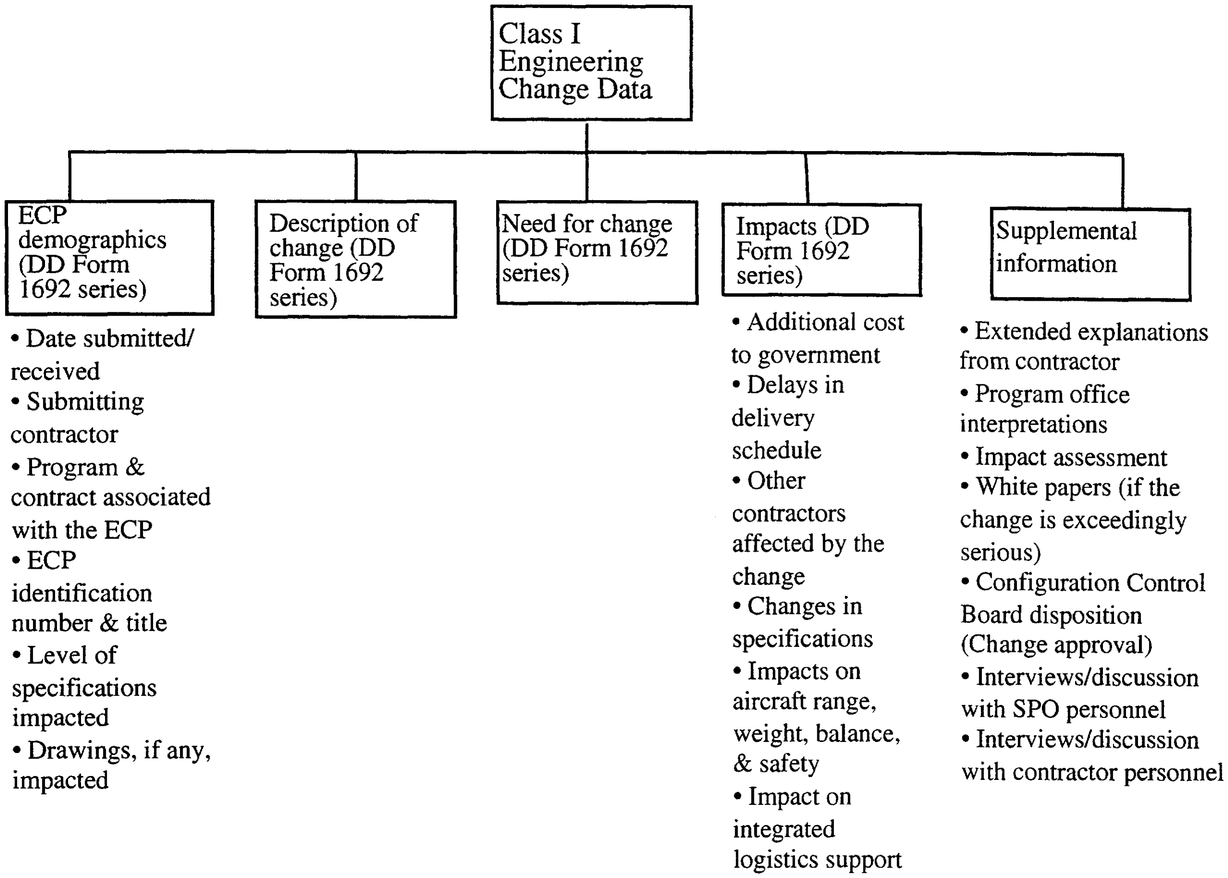


Figure 3-2: Elements of engineering change data

The engineering change data collected for this research were based mainly on the entries on DD Form 1692 series of contractor-submitted Engineering Change Proposal (ECP) forms. The ECP forms provided demographic data about the engineering changes. Important examples of demographic data found on the ECP forms include: date of submission to the program office, ECP identification and title, and levels of contracted specifications affected by the engineering change. Two entries on the forms that were of particular interest to this research were the "Description of Change" and "Need for Change" entries. They usually describe the background of the engineering change and the relevant system and subsystem, and the reason(s) the engineering change was necessary. The "Impacts" entries address cost to the customer due to the engineering change, possible delivery schedule delays, and specifications affected. Other impact areas also addressed by the ECP forms include aircraft performance (if applicable), and integrated logistics support. Supplemental information came from a variety of sources. For example, contractor may submit extra pages to further explain the cause of the engineering change. On the other hand, the program office may attach its own interpretation of the engineering change to the ECP file. Furthermore, SPO Configuration Control Board (CCB) decision regarding the approval of an engineering change was usually recorded in the ECP file. Finally, as collected for this research, notes from interviews and discussions held with government and contractor personnel regarding a specific engineering change were kept with other data for that engineering change.

Several special aspects of the data should be noted. First, not all entries on the submitted ECP forms were filled out. For example, when no actual product exists, an engineering change can only apply to the documents describing the design of the product. Consequently, the "retrofit labor hour" entry on the ECP form would be left blank. Second, it is extremely important to note the type of cost identified in the ECP. Such cost data only capture an increase or decrease in cost for the government; they do not account for the cost increase or decrease in cost borne by, or internal only to, the contractor. In particular, it is not clear in these cases how the costs are truly allocated or where the costs are actually borne.

3.2.2 Systems and Subsystems Data

Data pertaining to specific systems and subsystems provided a conceptual understanding of the functionalities, physical configurations, and development processes of the products in the three programs studied. Consequently, it also provided some technical appreciation for the challenges of designing, producing, and fielding the products. Figure 3-3 provides a summary of the database developed at the system and subsystems level. Sample questions that guided interviews and discussions with government and contractor personnel are provided in Appendix C.

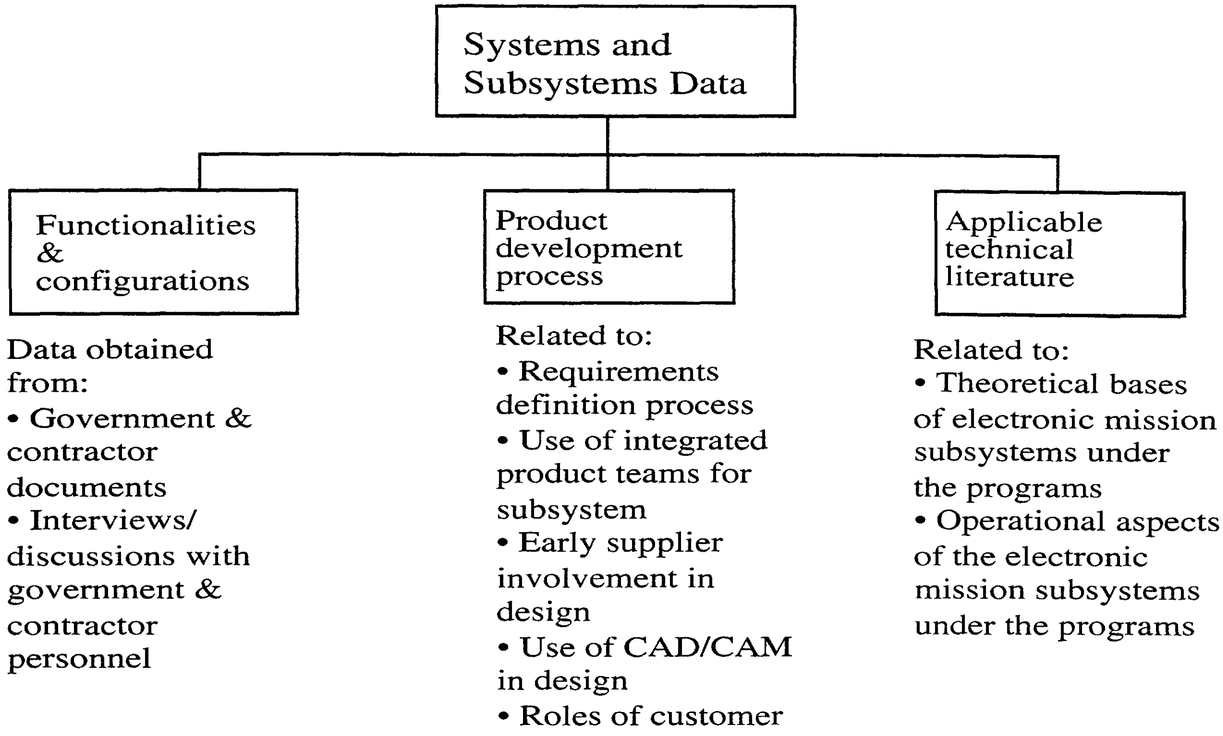


Figure 3-3: Elements of systems and subsystems data

The data on systems and subsystems were obtained from three sources. First, written documents provided by the SPO and contractors described system functionalities and physical configurations. Second, interviews and discussions with government and contractor personnel provided insight into the background of the respective system development efforts. On many occasions government and contractor personnel provided valuable clarification of the written material. Third, the technical publications describing the systems and subsystems enabled a deeper understanding of the engineering changes.

3.2.3 Program Data

Data pertaining to each of the three programs enabled a clear view of the roles and responsibilities of the three individual program offices, the user community, the prime contractors, and subcontractors (suppliers) in the product development process. In addition, the program-level data provided a description of how the various parties involved in product development on these three programs interacted with each other. Figure 3-4 shows the composition of program-level data.

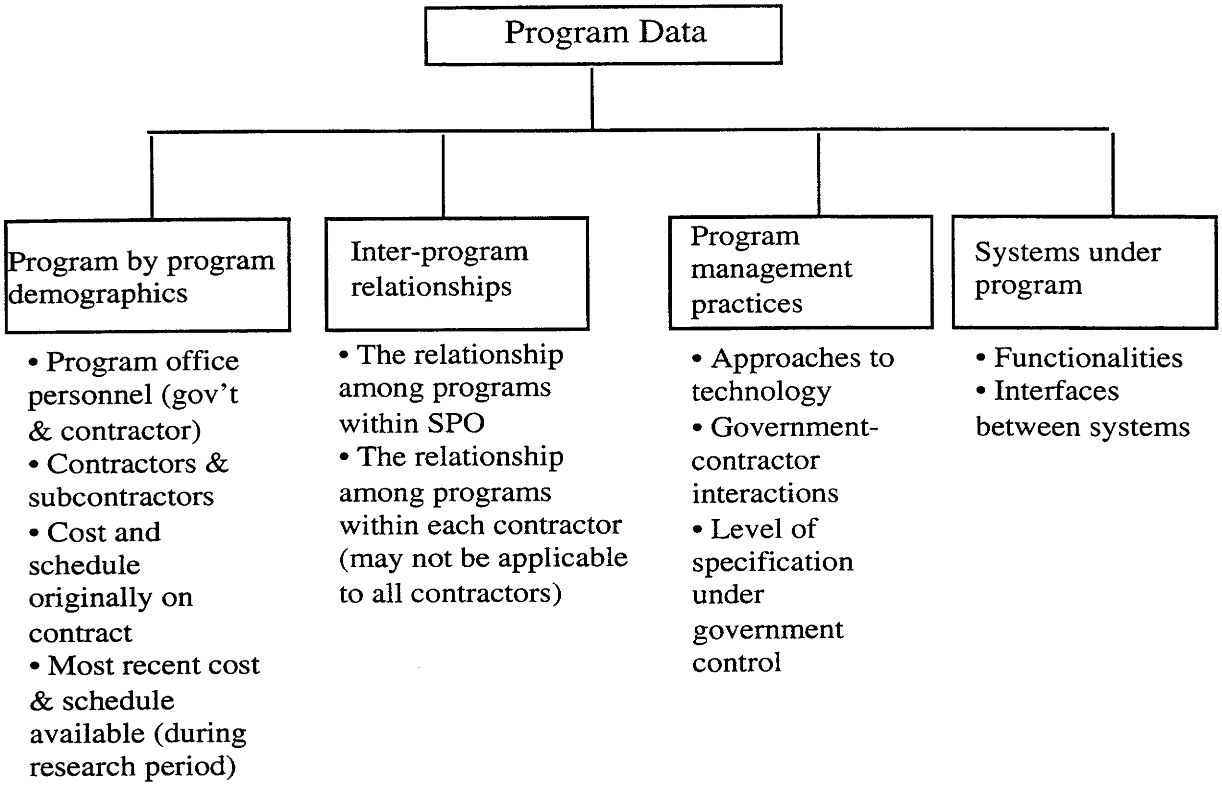


Figure 3-4: Elements of program data

The purpose of the types of data listed under the two left-hand-side boxes in Figure 3-4 is to understand the background of the three case-study programs from the perspectives of both the contractors and the government program offices. On the government side, the data are expected to provide a working understanding of the interactions among the program offices under the same SPO. The inter-program relationships are important because they may have played a role in driving the need for engineering changes. Furthermore, the cost and schedule data were obtained from contract cover pages and updates at the program offices, as well as from other program-related documents.

The two right-hand-side boxes in Figure 3-4 capture the inner workings of each program. Similar data from the contractor perspective were obtained as part of the data collected at the system and subsystems level, as summarized in Figure 3-3 and Appendix C.

3.2.4 SPO Data

SPO data represent the highest level of data in the hierarchy discussed at the beginning of Section 3.2. Figure 3-5 shows the elements of data collected at this level.

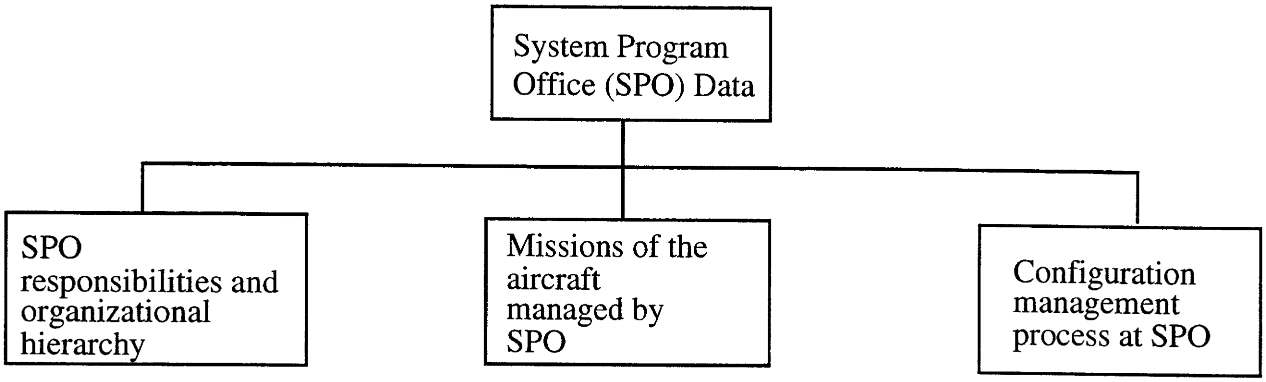


Figure 3-5: Elements of SPO data

SPO data provided high-level insight that enabled an understanding of the context of the other levels of data discussed earlier. In general, the descriptive data addressed the functioning of the System Program Office, and how the individual programs fit within the SPO. In addition, written information also described, in general terms, the missions performed by the aircraft managed by the SPO. Finally, the SPO-level data also included explanations of the configuration management process.

3.3 Framework for Categorizing Causes of Engineering Changes

This section introduces the framework used in this research for categorizing the primary causes[61] of engineering changes. One of the characteristics of research using archival data, such as the research documented in this thesis, is the need to translate the written records "into quantifiable indices of some general concepts."[62] The proposed framework is based on the review of existing frameworks found in the literature and in practice, as documented in Section 2.5.

---

[61] The term "primary causes" is used to underscore the observation made during the data collection process that in many cases a combination of causes, not a single cause, led to an engineering change. When "cause" is used, it should be understood to be the primary cause.

[62] Judd, Charles M., Eliot R. Smith, and Louise H. Kidder. *Research Methods in Social Relations*, 6th ed. Fort Worth, TX: Harcourt Brace Jovanovich College Publishers, 1991. p.289.

The objectives of the research and the review of existing frameworks suggested that the framework proposed here should encompass the following high-level causal categories: (1) requirements-related issues; (2) the need to fix deficiencies; (3) program interaction; (4) technological changes; and (5) documentation changes. Since one of the objectives of the research was to understand the causes of engineering changes, the causal categories should explain why the engineering change was needed, not what the engineering change was trying to accomplish[63].

3.3.1 The Framework for Categorizing Causes of Engineering Changes

Some of the high-level causal categories listed above appeared to be too broad to be useful in explaining causes of engineering changes in terms of the specific characteristics of the three case-study programs. For example, it was not apparent whether "requirements-related issues" meant requirements definition problems, or shifts in user requirements. Similarly, "program interaction" needed to be turned into more specific components. Therefore, appropriate decomposition of these high-level causal categories was necessary for this research. Table 3-2 shows the resulting framework that was used in this research to categorize the causes of engineering changes. The rationale for this categorization system is explained below.

---

[63] The requirement is based on Balcerak, K. J. and B. G. Dale. "Engineering change administration: the key issues." *Computer-Integrated Manufacturing Systems*, Vol. 5, No. 2, 1992. pp.125-132, where the authors made a distinction between the purpose and the cause of an engineering change.

1	**Requirements definition issues***
	A. Traceable to program initiation B. Traceable to a previous change
2	**Changes in needs***
	A. New needs identified B. Needs definitized
3	**Need to fix deficiencies**
	A. Modify design or product
4	**Government-prime interactions****
	A. Contracting/program arrangement B. Overly stringent specifications
5	**Program-program interactions****
	A. Design baseline shift in a predecessor program B. Program reprioritization
6	**Funding reduction after program start****
7	**Technology changes**
	A. Take advantage of advances in a certain area B. React to unfeasibility/obsolescence C. Change requirements to acknowledge capabilities/feasibility
8	**Need to change documentation**
	A. Synchronize paperwork
	B. Rescheduling tests
	* These 2 categories correspond to "Requirements-related issues".
	** These 3 categories correspond to "Program interaction".

Table 3-2: Framework used for categorizing causes of engineering changes

Requirements Definition Issues

This category captures engineering changes that can be linked to shortcomings in the requirements generation/definition process, and is one of two causes that could be related to the "requirements-related issues" listed above. Grady[64] suggested that necessary design changes to rectify failure to meet customer authenticated requirements "can be reduced by insisting on the discipline that requirements be developed before design is accomplished and by making sure that design personnel and teams are aware of and understand the requirements."[65] Shortcomings of the requirements generation process at the beginning of a program can sometimes be evident in

---

[64] Grady, Jeffrey O. *System Requirements Analysis.* New York, NY: McGraw-Hill, Inc., 1993. pp.79-80.

the contractor-submitted ECP forms, or they can be inferred based on interviews with government and contractor personnel familiar with the earlier phases of the program[66].

An engineering change may also be an unintended result of implementing a previous engineering change. Grady[67] noted that unintended consequences would result when implementing an engineering change whose requirements are not adequately understood. Since this phenomenon is related to the understanding of requirements before carrying out tasks, the primary cause of an engineering change attributable to the implementation of a previous engineering change would be placed in this category.

Changes in Needs

This category of causes, the second of the two which corresponded to the original "Requirements-related issues" listed above, is intended to capture the contribution of changes in user needs over time to engineering changes in a program. These changes in user needs may include the necessity to respond to improved enemy capabilities[68], and/or additional needs that did not exist at program initiation[69]. Furthermore, the user community may already have identified particular needs, but may have opted to learn more about the need before committing to a subsystem design. For example, changes in training and support equipment requirements may be due to this reason[70].

Need to Fix Deficiencies

This particular category accounts for engineering changes reflecting the fact that in the development and production of complex systems, it is unrealistic to expect absolutely no mistakes. Engineering changes implemented to correct mistakes that existed despite the

---

[65] Grady: 1993, pp.79-80.
[66] The observation is based on researcher's experiences in conducting the research.
[67] Grady: 1993; p.80.
[68] Grady: 1993, p.80.
[69] Beam, Walter R. *Systems Engineering: Architecture and Design*. New York, NY: McGraw-Hill, Inc., 1990. p.11.
[70] The example is based on observations made while collecting ECP data, and on interviews with contractor personnel.

thoroughness of the requirements definition process and the degree of dedication of the personnel are captured in this category.

Government-prime Interactions

This category addresses issues similar to those identified by Fricke et al.[71] as "Planning/management factors" and similar to the contractual arrangement issues alluded to in MIL-STD-480B ECP Justification Codes[72]. One of the intentions of the research is to study the contributions of government program management practices/decisions to engineering changes. In some cases, the government may rely on a single prime contractor for development and production phases of a program. In other cases, the government may choose to have a single prime contractor during development, and multiple prime contractors during production. In yet other cases, the government may choose to be the integrator during the development phase and manage multiple prime contractors. A question of interest is whether and how such different arrangements may drive the need for engineering changes.

Another issue related to the way the government interacts with its contractors is the stringency of the contractually imposed specifications. For example, the government may dictate how requirements are to be met, with any permanent deviation from a "how-to" requirement requiring an ECP[73]. It would also be of interest to know the extent to which these how-to specifications might drive the need for engineering changes.

---

[71] Fricke, Ernst, Bernd Gebhard, et al. "No Innovation without Changes, but..." *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. p.602.

[72] MIL-STD-480B Section 5.1.3.

[73] An interview with the configuration manager on Program A underscored the distinction between a deviation, a waiver, and an ECP. Deviation is a temporary change from specifications during development, i.e., contractor will return to following the contracted specifications. Waiver is permission to deliver items that deviate from specifications, and contractor will repair the deviations later. ECP makes both permanent.

Program-program Interactions

This category addresses organizational coordination issues similar to those identified by Fricke et al.[74] According to observations made while collecting ECP data, the SPO may be responsible for a number of on-going acquisition programs that began at different times. When the design of a subsystem in one acquisition program closely follows that of a subsystem in an earlier program, the engineering changes in the earlier program may impact the later program. Thus, how engineering changes in one program result in engineering changes in a subsequent program is a question of interest to this research.

A System Program Office (SPO) is responsible for all programs and related assets (e.g. test equipment) it manages. The SPO may occasionally reprioritize tasks across different programs. When different programs share the same test assets, for example, reprioritization may result in the higher-priority program making earlier use of the test assets. Since the test schedule may be included as a contracted requirement, the temporarily lower-priority program may need to make an engineering change to modify the test schedule[75]. How similar interactions drive the need for engineering changes is yet another category of causes of engineering changes which is important to understand, particularly since it may shed light on program management practices of the government.

Funding Reduction after Program Start

Gansler[76] has argued that a cut-back in military expenditures in a current year by reducing funding for one program would not only affect that program in later years, but would also affect other programs in the current and later years. It may become necessary for some of the affected programs to change their requirements in response to the funding reduction. These requirements changes may be implemented via engineering changes. This category is another possible cause of engineering changes relevant to this research.

---

[74] Same as Footnote 71

[75] Testing is part of verification, which is a systems engineering task.

Technological Change

The contribution of changes in technology to the need for engineering changes is also one of the factors important to this research. Fricke et al. have named "Technical factors" as one of the three broad causal categories for the purpose of classifying the causes of engineering changes.

The data collection effort for this research has indicated at least three ways in which engineering changes may come about because of technological changes. First, the contractor or the customer, which could be the user community or the acquisition community, may choose to incorporate a more recent technology into a design or an existing product for a variety of reasons including cost savings, increased performance, or ease of manufacturing. Second, there may be no choice but to incorporate a more recent technology because the various subsystems, components, and test equipment embodying older technology have become obsolete, or would be prohibitively expensive to acquire and sustain. Third, the customer, faced with the prohibitively high temporal and monetary costs of reaching the original performance expectation, may modify requirements to accept a smaller, more realistic, performance improvement.

Need to Change Documentation

Adopted from Code A of MIL-STD-480B ECP Justification Codes, this causal category accounts for engineering changes directly due to the need to coordinate documentation. Furthermore, the need for engineering changes due to any rescheduling action in the case-study programs, except for those that can be substantiated as being due to program reprioritization, would be placed in this category, especially when such engineering changes cannot be attributed to another cause.

---

[76] Gansler, Jacques S. *Affording Defense*. Cambridge, MA: The MIT Press, 1991. pp.102-103.

3.3.2 Evaluation of the Framework for Categorizing Causes of Engineering Changes

An evaluation of the framework for categorizing causes of engineering changes was done according to the three criteria developed in Section 2.5. The following paragraphs describe the results of this evaluation.

Examine a Variety of Product Development Issues

The framework meets this criterion for two reasons. First, the framework is not limited to the design-manufacturing interface. Second, the framework explicitly enables the study of how various product development practices of both the government program office and the contractors might contribute to engineering changes.

Provide a Systems View of US Defense Aerospace Product Development

This criterion is met because the framework studies the roles of, and interactions among, the various communities in defense aerospace product development as possible contributors of engineering changes. For example, the framework studies the extent to which changes in user needs might contribute to the engineering changes on a program. Similarly, the framework also studies the interactions among different communities - the program offices, the prime contractors, and the different programs within the same SPO - as possible contributors of engineering changes.

Extract Lessons Learned

As in the case of the existing frameworks reviewed in Chapter 2, lessons learned can be derived from analyses employing this framework, as long as corroborative data can be obtained. This research seeks to identify product development practices that help to reduce certain engineering changes. Therefore, the framework should be capable of relating the causes of engineering changes to specific activities performed and decisions made during the development of a product.

3.4 Framework for Categorizing Impacts of Engineering Changes

This section presents the framework employed in this research for categorizing the impacts of engineering changes. The framework is largely based on the literature and practices discussed in Section 2.6.

Since engineering changes differ in their scope of impact, the framework must permit an examination of the impacts of engineering changes at an appropriate level of detail (or generality) to enable cross-program comparison. For example, engineering changes during the early design phase of a program would have no impact on the physical manifestation of the product since no product would yet have been built in this phase. Also, an engineering change that calls for the repair of certain components to be done by the user community would include detailed estimates of labor hours required. The framework must provide meaningful cross-program comparisons in the presence of such differences.

3.4.1 The Framework for Categorizing Impacts of Engineering Changes

Table 3-3 shows the framework used in this research for categorizing the impact of engineering changes. Notable features and each impact area, or domain, are explained below.

1	**Near-term cost impact**
	• More cost with engineering change than without • Less cost with engineering change than without • Not impacted
2	**Program schedule**
	• Delayed • Advanced • Not impacted
3	**Product performance with respect to expectation**
	• Increase • Decrease • Met shifted expectation with engineering change • Met existing expectation with engineering change • Not impacted
4	**Primary impact on prime contractor's work**
	• Rework • New work • Less work • Not impacted
5	**Primary impact on supplier(s)' work**
	• Rework • New work • Less work • Not impacted
6	**Impact on other program offices in SPO**
	• Yes • No
7	**Unanticipated engineering changes over the same issue in the same program**
	• Yes • No

Table 3-3: Framework used for categorizing impacts of engineering changes

A number of features of this framework are noted. First, the impact areas - cost, schedule, and performance - largely address "things"[77] related to a program. Second, the prime contractors, the suppliers, the user community, and the program office largely address the "people"[78] aspects of the program. Third, since the program office responsible for processing an engineering change always does more work, as observed during on-site data collection at the SPO, tracking how that program office is impacted would not be very illuminating. Therefore, "impacts on program office's work" is not among the impact areas studied. However, it would be illuminating to study how an engineering change might impact other program offices in the same SPO, and this impact area is included. Finally, the user community is not studied separately because it is closely coupled with the performance of the product, and interviews with the user community were not possible within the confines of the research.

The impact areas are discussed below. The examples given in each discussion are based on ECP descriptive data collected for this research.

Near-term Cost Impact

This impact area captures the effects of engineering changes on the cost variable. For the purpose of this research, cost may be incurred by any party including the customer, the prime contractor, or the suppliers (subcontractors). An engineering change can result in cost increases borne by the customer in the near-term, but can result in future product life cycle cost savings. Therefore, for the cost variable, because of uncertainty about future cost savings, the research focuses on the near-term cost impacts of engineering changes. In this context, the research attempts to answer the following question, "As a result of the engineering change, was the cost of the program higher or lower than it otherwise would have been without the engineering change, or was it not impacted at all?" For example, a redesign to meet requirements, although not paid for by the customer, would translate directly into a cost increase for the contractor. The cost of the

---

[77] The idea was suggested by a discussion on fundamentals of complexity in Flood, Robert L. & Ewart R. Carson. *Dealing with Complexity: An Introduction to the Theory and Application of Systems Science*. New York, NY: Plenum Press. 1993. p.24.
[78] Flood & Carson: 1993, p.24.

program, therefore, would likely be higher. Alternatively, an engineering change made to modify the requirements, terminate design activities, and accept obtainable capability would likely make the program cost less than it otherwise would have without the engineering change.

It should also be noted that the only cost figure reported on the ECP submittal form is the cost to government. The existence of any additional cost to contractor, such as in the case where the contractor must correct a product defect, can only be inferred from descriptions of the engineering change.

Program Schedule

This impact area addresses the overall program schedule, rather than the schedules of individual tasks in a program. In the course of the research, specific cases have been encountered where additional tasks could be performed without jeopardizing program schedule. It needs to be clearly understood that this impact area, focusing on impacts of engineering changes on program schedule, does not address the broader and different question, "What are all the sources of program schedule delays?"

Product Performance with respect to Expectations

This impact area bridges the "things" and "people" aspects of a program because the user community (people) is very closely associated with the performance of the product (thing). The increase in product performance beyond expectations addresses the "delight the customer"[79] aspect of product development. An example of decrease in product performance with respect to expectations would be engineering change made to accept an achievable product performance that is lower than originally expected or specified. Engineering changes can also be made to meet shifting expectation. For example, new training equipment may be added to the overall system design to address new training needs that may not have been anticipated earlier. Furthermore, engineering changes can also be made to meet existing expectations. Fixing a deficiency would be

---

[79] "Delight the customer" is a concept about doing a little extra for the customer. The concept is discussed by Boppe, Charles W. in MIT course 16.870 Aerospace Product Design. Fall 1996.

such an example. Finally, engineering changes may not necessarily impact product performance, such as in the case of engineering changes made to documentation so that the documentation would match the actual design.

Primary Impact on Prime Contractor's Work

This impact area studies whether the prime contractor must do rework, more work (expanded contract scope), or less work (a relief from some contracted requirements) as a result of an engineering change. Rework may correct something that was not done correctly before. It would encompass redesigns and documentation coordination. New work is something the contractor was not required to do prior to the engineering change. An example would be to produce new training simulators in order to meet evolved user requirements. An example of an engineering change resulting in the prime contractor having to do less work would result from modifying requirements to accept realistically obtainable capabilities. In such a case, the engineering change would relief the prime contractor from having to carry out more design tasks necessary to meet the original requirements.

Primary Impact on Supplier(s)' Work

This impact area studies whether the suppliers must do rework, more work (expanded contract scope), or less work as a result of an engineering change. The definitions of the types of impact (i.e. rework, new work, and less work) are the same as those stated in the impact area addressing the effects of engineering changes on the prime contractor's work.

Impact on Other Programs

In Table 3-2, one of the hypothesized causes of engineering changes was the interactions among programs under the SPO. This impact area explores a similar issue of whether each engineering change from one program has impacted another program under the SPO in any way.

Unanticipated Engineering Changes in the Same Program

This impact area intends to quantify the extent to which engineering changes subsequently lead to additional unanticipated engineering changes. Whether an engineering change was an unanticipated result of a previous engineering change can be determined from the description of the engineering change, supplemented by government and contractor documents and interview results. This impact area reflects "cause-effect net of changes" concept that has been advanced by Fricke et al.[80]

3.4.2 Evaluation of the Framework for Categorizing Impacts of Engineering Changes

All three criteria used in Section 3.3.2 to evaluate the framework for categorizing causes of engineering changes can be applied to evaluate the framework for categorizing impacts of engineering changes.

Examine a Variety of Product Development Issues

The proposed framework is fairly general and is not limited to the design-manufacturing interface, which has been the primary focus of previous studies on engineering changes. The impact areas have been broadly defined so as not to stipulate the life cycle phase or organizational interface to which the framework may be applied.

Provide a Systems View of US Defense Aerospace Product Development

The framework accounts for the impacts on the products and the communities involved in defense aerospace product development. Although the impact on the work of each program office is not explicitly addressed (because its work always increases with each engineering change, as observed during the on-site research at the SPO), the impacts on the acquisition community are examined via the impact of an engineering change on other programs, and whether an engineering change led to additional unanticipated engineering changes.

---

[80] Fricke et al.: 1997, p.601.

Extract Lessons Learned

The framework satisfies this criterion by having the potential to show how the impacts of engineering changes may vary from program to program. The differences would have to be explained using program-level data. For example, it is possible that one program had a significantly higher percentage of engineering changes associated with program schedule delay than did the other two programs, the difference must be explained using knowledge about the programs, thereby inferring lessons learned about product development.

3.5 Data Analysis and Interpretation Process

Efficacy of the findings of this research depends in large part on consistency in identifying the primary cause and impacts of each of the 118 engineering changes across the three case-study programs. Uniform analysis of the data according to the frameworks presented in Sections 3.3 and 3.4 was the mechanism for assuring consistency. This section focuses on how causes and impacts of engineering changes are determined, and on how the major conclusions are drawn from consistent analysis of quantitative data and program descriptions.

3.5.1 Identifying and Coding the Causes of Engineering Changes

For the purpose of data analysis in this research, the framework presented in Table 3-2 provides a set of bins into which each of the 118 engineering changes can be placed. The most important cause of each engineering change was identified based on written and verbal inputs from the pertinent ECP documents, the government program office, and the contractors. The inputs were first recorded in one row (one row for each engineering change) in an appropriate EXCEL file (one file for each program), and then the primary cause was determined and coded according to Table 3-2. The rationale for the determination was recorded at the end of the row, along with any other remarks. This process was repeated for all 118 engineering changes. The percentage of engineering changes due to each cause was then computed.

Several difficulties were encountered while implementing this procedure. Sometimes the program office and the contractor provided conflicting explanations of why an engineering change was necessary. In these cases, the determination relied as much as possible on documented records. Also, there were cases when two causes seem equally plausible based on the weight of the available evidence. In such cases, the primary cause was judged to have been the one that was more likely to have been present earlier in time, to the extent that this judgement was supported by data. In addition, there were cases in which it was difficult to distinguish between an engineering change that was due primarily to changes in user needs and another engineering change that was due primarily to changes in technology. However, this ambiguity could usually be resolved by a close examination of the documented data. If it could be determined that the engineering change addressed a user need by incorporating newer technology, then the change was attributed to changes in user need. On the other hand, before an engineering change could be ascribed to changes in technology, data was required to indicate that a certain party in the product development process (e.g., customer, prime contractor) actively sought out the newer technology. Another problem occurred when two prime contractors each submitted an ECP[81] to address an issue that pertained to both of them. In such cases, it was necessary to determine which ECP would not have been filed had it not been for the dual-prime contractual arrangement. The one that must be filed because of the dual-prime arrangement was coded as having been due to "government-prime interactions." The other engineering change was treated as if it were the only engineering change addressing the issue. Finally, an engineering change file alone was sometimes insufficient to justify a determination of the primary cause. In such cases it was necessary to rely on the interview results.

3.5.2 Identifying and Coding the Impacts of Engineering Changes

The data coding process for impacts of engineering changes was similar to that for the causes of engineering changes. However, one difference was that an engineering change could affect all seven impact areas identified in Table 3-3, whereas each engineering change could be ascribed to only one primary cause. Therefore, it was necessary to examine each engineering change seven times, once for each of the seven impact areas, to look for evidence - from ECP

---

[81] They are supposed to do this if the specifications under their control are affected by the engineering change.

submission, and written and verbal inputs from the government and contractors - that may indicate how each area might have been impacted. For each engineering change recorded in a row in an EXCEL file, every cell in that row was given a justification as to why each specific impact was identified and coded.

The degree of difficulty in identifying and coding the impacts of engineering changes varied according to the impact area in question. For example, it was relatively straightforward to determine whether an engineering change from one program impacted another program. On the other hand, it was more difficult to determine the impacts of engineering changes on product performance with respect to expectations because of the subjective nature of such impacts.

3.5.3 The Development of Lessons Learned

Graphical representations of data regarding the causes and impacts of engineering changes on the three case-study programs enabled the development of lessons learned in two ways. First the trends in the graphical representations of engineering change data from each case-study program, combined with pertinent descriptive data, provided insights about certain aspects of that program. Second, the graphical representations of the engineering change data collected for this research, combined with descriptive data about the three programs, enabled cross-program comparisons that led to some insights that may be applicable to broader aspects of defense aerospace product development.

3.6 Chapter Summary

This chapter provided the background information on the implementation of the research in order to enable the reader to understand and judge the findings that follow in subsequent chapters. It has provided the fundamentals of the case study research that included the data sources, and the characteristics of the elements of the database. Next, it introduced the frameworks for categorizing causes and impacts of engineering changes that were used for translating text-based data into quantitative data. Finally, the chapter outlined the process via which the translation was implemented and the findings were developed.

It should be stressed that the database and the findings presented below pertain to three specific case-study programs. Therefore, generalizations from the results of this analysis to the entire US defense aerospace industry should be carefully qualified.

This page is intentionally left blank.

4. Program Characteristics and Causes of Engineering Changes

This chapter describes the case studies performed in the research, with the goal of enabling an understanding of the relationships between program characteristics and the causes of engineering changes. Section 4.1 provides basic program data such as cost, schedule, and level of specifications controlled by the customer during development phase. Sections 4.2, 4.3, and 4.4 relate program characteristics to causes of engineering changes. Section 4.5 presents various causes of engineering changes, aggregated across the three programs, in order to identify the dominant causes. Finally, Section 4.6 summarizes the findings.

The framework used in this research for categorizing causes of engineering changes is referred to extensively for detailed explanation of the data presented below. Therefore, Table 3-2 is repeated here for the convenience of the reader.

1	**Requirements definition issues**
	A. Traceable to program initiation B. Traceable to a previous change
2	**Changes in needs**
	A. New needs identified B. Needs definitized
3	**Need to fix deficiencies**
	A. Modify design or product
4	**Government-prime interactions**
	A. Contracting/program arrangement B. Overly stringent specifications
5	**Program-program interactions**
	A. Baseline shift in a predecessor program B. Program reprioritization
6	**Funding reduction after program start**
7	**Technology changes**
	A. Take advantage of advances in a certain area B. React to unfeasibility/obsolescence C. Change requirements to accept capabilities/feasibility
8	**Need to change documentation**
	A. Synchronize paperwork B. Reschedule tests

Table 4-1: Framework used for categorizing causes of engineering changes

Three cautionary remarks are appropriate at this point. First, the temptation to judge the programs' technical and programmatic performance beyond the data shown in this research should be resisted. This research is not intended to provide a comprehensive review or critique of the programs. Second, the temptation to extrapolate the findings to other programs or sectors of the defense aerospace industry should also be resisted. It is important to recall that all three case-study programs are aircraft programs in electronics sector of the aerospace industry, so generalizations beyond that sector should be viewed with caution. Finally, there is no one-to-one correlation between Programs A, B, and C, and Contractors X, Y, and Z. In other words, Contractor X cannot be assumed to be the sole prime contractor responsible for Program A.

The quantitative data presented below are based on ECP files, supporting documents, and interviews with government and contractor personnel. The following sections represent the researcher's understanding of the various details of the three programs, and the responsibility for any error in interpretation rests fully with the researcher.

4.1 Program Parameters

Table 4-2 summarizes the cost-to-customer, program duration, and levels of specifications controlled by the customer for each program's development phase. These three items are explained in turn.

	Nominal development & production cost (Millions of dollars)	**Additional customer expenses for add-on equipment (Millions of dollars)**	**Nominal development time (Months)**	**Estimated actual development time (Months)**	**Program duration as of mid 03/1999 (Months)**	**Levels of specifications controlled by customer during development phase**
Program A	$280[1]	$254[4]	36[7]	84[10]	144[13]	All[16]
Program B	$664[2]	$93[5]	50[8]	84[11]	116[14]	All[17]
Program C	$1240[3]	$81[6]	57[9]	57[12]	66[15]	System Specification (SS) & Mission System Specification (MSS) only[18] (2 top-level specifications)

1 Program A internal presentation & original contract (development & production) cover sheets.
2 Development & production contracts cover sheets.
3 The estimate is based on figures published in applicable documents.
4 ECP data entries.
5 ECP data entries.
6 ECP data entries
7 Program A contractor memorandum.
8 Contractor Z personnel input.
9 Program calendar up to the delivery of first aircraft.
10 Effective date of production contract used as the end of full-scale development (FSD).
11 Effective date of production contract used as the end of FSD.
12 Same as Note 9, plus program office input that there has been no delay.
13 From effective date of FSD contract to the mid-March 1999.
14 From effective date of FSD contract to the mid-March 1999.
15 From date of contract of Program C studied until March 1999.
16 Program office & contractor personnel input.
17 Program office & contractor personnel input.
18 Program office & contractor personnel input.

Table 4-2: Basic program parameters

The cost data in Table 4-2 include only cost to the customer. They exclude, for example, uncompensated contractor cost for implementing an engineering change. In addition, the user community can issue contracts of limited dollar amounts[82] without program office approval; and the exact dollar amounts of these contracts are also excluded due to data unavailability.

Development, as opposed to production, schedules are of interest because the research seeks to understand the relationship between product development and the need for engineering changes. A special note on schedule pertains to the parallel nature of tasks. For example, a task may need to be redone by implementing an engineering change, but this does not mean that every such change would delay the entire program.

Since the last column in Table 4-2 is particularly important for understanding program comparisons based on quantitative results, the terms "system specification (SS)" and "mission system specification (MSS)" warrant some discussion[83]. The term "system specification" usually refers to design documents describing the high-level functional and performance characteristics of an overall product developed to carry out and support a mission. The "mission system specification" usually refers to design documents describing the functional and performance characteristics of only the elements of the overall product that actually carry out the mission. At levels lower than the MSS, there are specifications that describe each of these elements and their components. In the three case-study programs, since engineering changes in Program C that were relevant only to lower-level specifications were unavailable, the exclusion of engineering changes in Programs A and B that were relevant only to lower-level specifications is necessary as a normalization step to ensure the comparability of results across all three programs.

In the following sections the three programs are examined individually, before the results are aggregated across all three programs.

---

[82] Done via Engineering Services Task (EST) contracts.

[83] The definitions of terms are based on Samaras & Czerwinski. *Fundamentals of Configuration Management.* New York, NY: Wiley Interscience. 1973, pp.53-57, and Blanchard, Benjamin S. *System Engineering Management.* New York, NY: John Wiley & Sons, Inc. 1991, pp.65-67.

4.2 Program A

4.2.1 Purpose and Scope

Program A was an upgrade program to integrate[84] four electronics mission subsystems into an existing fleet of mission aircraft, each of which carries a suite of mission subsystems. The program would enhance the existing fleet by improving the aircraft's target detection/identification, data processing, communications, and navigation capabilities.

4.2.2 Top-Level Description of Products

One of the four subsystems - designated as Subsystem A1 - was the target detection/identification system. Its design was based on an existing, technologically advanced device in service with another branch of the US armed forces. In that application, the device is operated in a stationary environment, but when integrated into Program A's aircraft, it was to operate from moving aircraft. Despite this and other differences in operational characteristics, the subsystem was thought to be 85% to 90% off-the-shelf (OTS) at the time Program A began. According to interviewed sources from multiple organizations and backgrounds, the subsystem today is considered to be 10% to 15% off-the-shelf and 85% to 90% developmental. The difference between the expected and actual development required on Subsystem A1 had significant implications for its manufacturer, a supplier to Contractor Z.

The second of the four electronics mission subsystems - Subsystem A2 - was a low-risk developmental item used for data processing. It was an upgrade of a subsystem in service on Program A's aircraft. With the upgrade, Subsystem A2 gained processing speed and capacity. During the course of Program A, a Subsystem A2 component, which interfaces with other informational subsystems on the aircraft, went through yet another upgrade. This last increment of upgrade made Subsystem A2 into an upgrade of an upgrade. The integration of Subsystem A2 into the aircraft was characterized as smooth, compared to that of Subsystem A1.

---

[84] Any "development" in this program could be thought of as the development of the subsystem to be integrated, and the way the integration was to be done.

Subsystem A3 was purchased by the customer, and turned over to Program A's prime contractor to integrate into the aircraft. It was a communications subsystem capable of securely sending and receiving data between a number of data senders and recipients. Similar to Subsystem A2, the integration of Subsystem A3 into the aircraft could also be characterized as smooth.

Finally, Subsystem A4 was added to provide navigation-related functions. Subsystem A4 was also purchased by the customer, and turned over to Program A's prime contractor to integrate into the aircraft. In addition to Program A's aircraft, Subsystem A4 was being added to a number of different fleets of aircraft serving many different needs. Similar to Subsystem A2, Subsystem A4 went through another upgrade during the course of Program A to increase its capabilities. Similar to Subsystems A2 and A3, the integration of this subsystem into the aircraft was also relatively trouble-free.

4.2.3 Product Development Process and Issues

The development phase of Program A began when concepts such as concurrent engineering (CE) and integrated product and process development (IPPD) were not used in the defense aircraft sector of the aerospace industry. The developmental work was done by a single prime contractor, Contractor Z, which had the responsibility for selecting suppliers to the program.

The suppliers of all the subsystems were deeply involved with the design of their respective subsystems (i.e., they were manufacturing products of their own designs, not those of the prime contractor's designs). Subsystems A3 and A4 were developed previously for other programs. Their "suppliers" were so called because the products were being integrated into Program A's aircraft, not because these companies were sub-contractors to Contractor Z.

For Subsystem A1, the supplier was the designer and producer of a device performing a similar mission in another military branch. In order for Subsystem A1 to perform as expected in an operational environment for which the original version was not designed, it was necessary to significantly redesign the off-the-shelf original. As Program A proceeded, the Subsystem A1 supplier became overwhelmed by the massive development effort required. Eventually, Contractor Z became very active in monitoring the design and verification processes of the supplier.

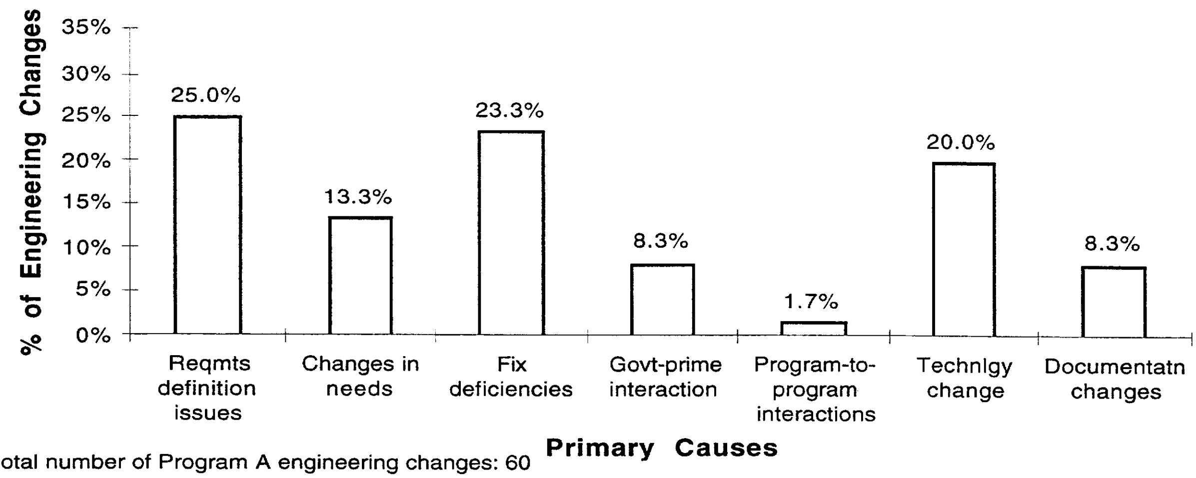
For Subsystem A2, the supplier (during development) was the original developer and manufacturer of Subsystem A2's predecessor. When Subsystem A2 entered its production phase, Contractor Y became another prime contractor on the program, and was responsible for selling the subsystem directly to the government (represented by the program office). The government in turn provided the subsystem to Contractor Z to integrate[85] into the Program A aircraft. There were, thus, two prime contractors in Program A, Contractor Y and Contractor Z. With two prime contractors, Contractor Y and Contractor Z, during the production phase of Program A, the changes in Contractor Y's Subsystem A2 product configurations could impact higher-level specifications, contractually under the custody of Contractor Z. When such a situation arose, each contractor had to submit an Engineering Change Proposal (ECP) to the program office. Therefore, two ECPs were necessary to deal with one engineering change issue. This situation in fact arose a small number of times in Program A.

4.2.4 Program A Causes of Engineering Changes

The results of the analysis showing the percentage composition of Program A engineering changes due to each primary cause are shown in Figure 4-1. These results can be further decomposed in two ways: the first is to decompose them into the causal subcategories shown in Table 4-1 and the second is to decompose them according to the four Program A subsystems.

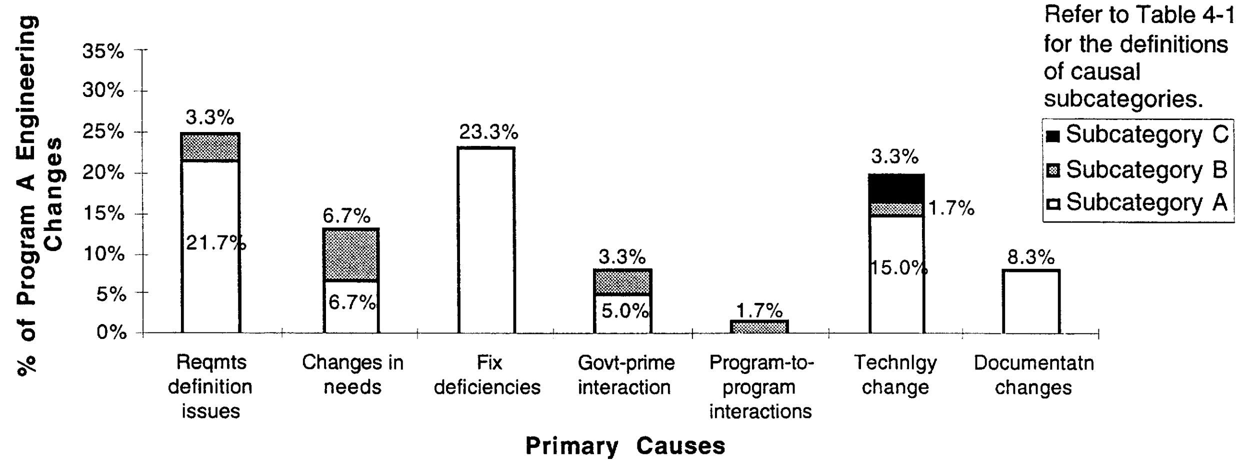
---

[85] This latter task was carried out with the user community.



Total number of Program A engineering changes: 60

Figure 4-1: Primary causes of engineering changes in Program A



Total number of Program A engineering changes: 60.

Figure 4-2: Breakdown of primary causes of engineering changes in Program A

Figure 4-1 and Figure 4-2 show that in Program A, the majority (68.3%) of engineering changes were due primarily to three causes: requirements definition issues at the beginning of the program, physical modifications made to fix deficiencies, and changes to take advantage of advances in technology. In Figure 4-2, it can be seen from the bar for requirements definition issues that only 3.3% of Program A engineering changes were due primarily to surprises resulting from previous engineering changes. This small proportion of engineering changes correspond to subcategory 1B in Table 4-1. In addition, nearly one-quarter of Program A engineering changes were due primarily to the need to fix unforseeable deficiencies. Furthermore, while most of the technology-related engineering changes shown in Figure 4-2 were made to take advantage of newer technology, a minority of them (accounting for 1.7% overall) were made in response to technological obsolescence, and a slightly larger minority (accounting for 3.3% overall) were made to accept obtainable capabilities by modifying requirements. These correspond to subcategories 7A, 7B and 7C, respectively, in Table 4-1.

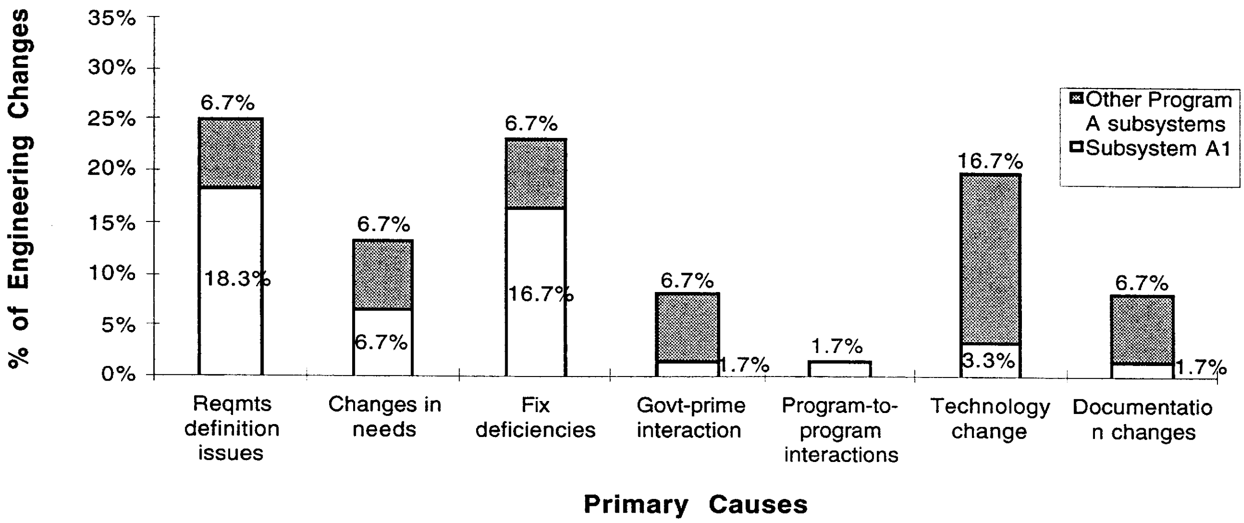
In addition, engineering changes that addressed changes in needs were due to foreign allies joining the development program, user community requests that had never surfaced before, and the modification of overall system configuration with updated simulators[86]. These primary causes correspond to causal subcategories 2A and 2B in Table 4-1.

The primary causes that are led to lesser percentages of engineering changes should also be discussed. Under government-prime interactions in Figure 4-2, 5% of engineering changes were due primarily to the fact that some Subsystem A2 changes during production required two ECPs, one from each of Contractor Y and Contractor Z. Without the dual-prime arrangement, only one engineering change would have been submitted by the prime contractor. Since there was a dual-prime arrangement during the production phase of Subsystem A2, two engineering changes were necessary when a change affected the specifications under the custody of each prime contractor. The rest of the engineering changes due primarily to government-prime interactions were made to relax some how-to specifications (subcategory 4B in Table 4-1). The single (1.7%) engineering change in Program A due primarily to program-to-program interactions was a change in system test schedule in order for a higher-priority test (from another program within the same System Program Office) to make earlier use of test resources. Finally, 8.3% of engineering changes in Program A were needed simply to match documentation describing the design with the actual design.

---

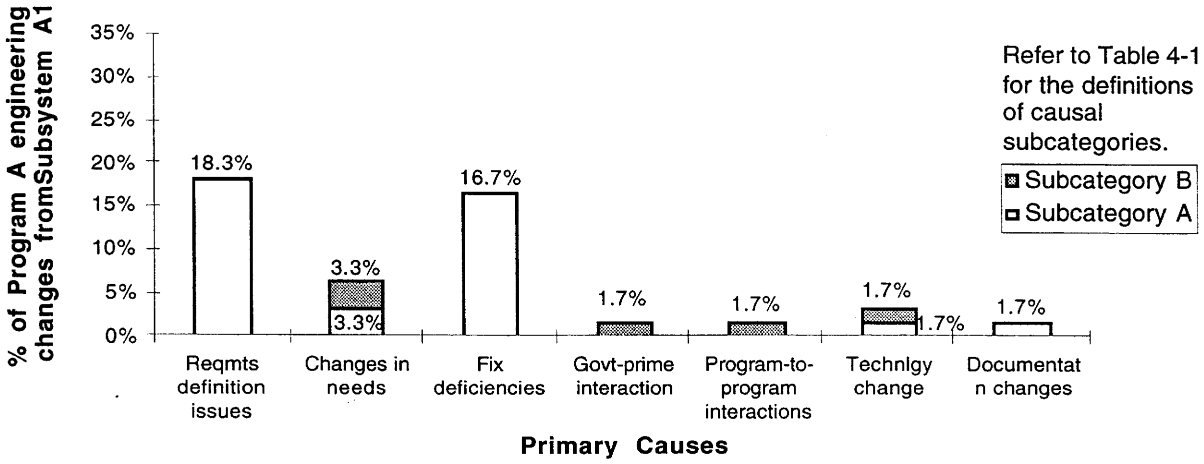
[86] Updated simulators were necessary so that operators can be trained to operate the new mission subsystems. The purchases of such equipment required engineering changes because the presence of the updated simulators modified the overall system that includes the aircraft, the mission subsystems, the operators, and the ground/support/training equipment.

If engineering changes represented in Figure 4-1 were to be decomposed into those pertaining and those not pertaining to Subsystem A1, it becomes clear in Figure 4-3 that Subsystem A1, which was one of four Program A subsystems, accounted for 50% of the total number of engineering changes in Program A. Figure 4-4 examines the primary causes of Subsystem A1 engineering changes in more detail.



Total number of Program A engineering changes: 60.

Figure 4-3: Dominance of Subsystem A1 in terms of Program A engineering changes



Refer to Table 4-1 for the definitions of causal subcategories.

30 Subsystem A1 engineering changes; percentages based on 60 Program A engineering changes.

Figure 4-4: Breakdown of primary causes of Subsystem A1 engineering changes

Figure 4-3 and Figure 4-4 show that Subsystem A1 accounted for high proportions of Program A engineering changes that were due primarily to requirements definition issues and the need to fix deficiencies. The former was traceable to the redesigns - actual redesigns of the product and revisions of portions of design documents to more correctly reflect user needs - carried out to modify the off-the-shelf system. The engineering changes that fixed deficiencies were implemented to correct recent producibility and reliability problems on Subsystem A1. Examples of these problems included cracked wire insulation, performance degradation due to reversed capacitor polarity in installation, and unlabeled cables.

4.2.5 Discussion

Several observations can be made based on the case study. First, despite the early involvement of the supplier of Subsystem A1 in Program A's development phase, there remained a large number of engineering changes that were implemented to adapt Subsystem A1's predecessor to a different, and much more demanding operational environment than the one for which it was originally designed. Second, the case study demonstrated the importance of understanding the operational environment requirements when it comes to the adaptation of off-the-shelf subsystems. Figure 4-3 shows that in terms of engineering changes, assuming a subsystem to be mostly off-the-shelf can lead to redesigns sufficiently substantial to dominate a program's efforts. Finally, it is observed that the combination of dominant causes of engineering changes in Program A reflected the program's particular characteristics.

4.3 Program B

4.3.1 Purpose and Scope

The purpose of Program B was to develop and integrate technology to increase the performance of a key electronics mission subsystem (Subsystem B1) on the aircraft. The program combined a number of smaller programs into one to enhance data acquisition capability, data processing speed and capacity, and human-machine interface. Also, although Subsystem B1 was extensively modified, some parts of it were to be left unmodified. Program B personnel interviewed at multiple organizations for the purposes of this research have noted that the program had significant software content.

4.3.2 Top-Level Description of Products

The main achievement of Program B was the increased performance of Subsystem B1, accomplished via the installation of an improvement kit. Elements of the improvement kit addressed the data acquisition capability, data processing speed and capacity, and human-machine interface aspects of the subsystem. Hardware aspects of data acquisition enhancement were accomplished by replacing older components with those of tighter tolerances and lower electronic noise. Data processing was improved with an all-new, larger and faster computer. Finally, the man-machine interface was improved by a totally-new operator's console, complete with dual displays. The improvement kit also included corresponding software updates. With the improvement kit installed, the subsystem would consist of some original components, some slightly updated components, and some all-new, state-of-the-art components.

4.3.3 Product Development Process and Issues

The study of Program B focused on full-scale development (FSD) and production phases. Several notable Program B product development issues include the way the program office interacted with the contractors during FSD, integration of key suppliers into product development, and the dependence of Program B's progress on that of Program A.

The customer, as opposed to a prime contractor, was the integrator during FSD, with two contractors serving as associate contractors. The goal of this contractual arrangement by the program office was to reduce cost; the program office did not have to pay one prime contractor to manage another as a supplier. The associate contractors were equal primes, although one contractor, Contractor Z, was responsible for meeting system level specifications[87], while the other, Contractor X, was responsible for meeting specifications up to a prime item[88] specification covering Subsystem B1. For Contractor X, the prime item specification was the "system-

---

[87] Those denoted as System Specification (SS), and Mission System Specification (MSS).

level"[89] specification. In terms of product architecture, Contractor X's product was to become part of Contractor Z's product. It must be emphasized that this situation is fundamentally different from one in which a development program uses two prime contractors to design equivalent but competing products with the goal of eventually downselecting to just one prime contractor.

An immediate consequence of the associate contractor arrangement was that when an engineering change affected specifications traceable to both contractors, each contractor had to submit an ECP addressing its portion of the change. This arrangement may have led to disconnects in requirements, especially during the development phase, when one contractor's product had to be installed into another contractor's product, with the customer assumed the task of integrating the products. Contractors X and Z, and the program office personnel met monthly at program management reviews (PMRs). During Program B's production phase, the production contract called for one prime contractor, and one of the two associate contractors in FSD became the key supplier to the prime contractor.

A prime-supplier relationship between the two contractors could still exist in substance, although not in name, since the early development phase, even though both were associate contractors in the strictly contractual sense. One way to consider the situation is to consider the relationship between the products of the contractors. When the product of one contractor becomes a part of the product of another, the former contractor could be considered a supplier. In the case of Program B, Contractor X could be considered a supplier to Contractor Z even though they were associate contractors during FSD. In this case, the key supplier and some of its lower-tier suppliers were involved in Program B development early on.

Finally, the third product development issue identified in Program B was the fact that the progress of Program B depended somewhat on that of Program A, since subsystems from both programs were onboard the same fleet of aircraft. The implication is that many changes in

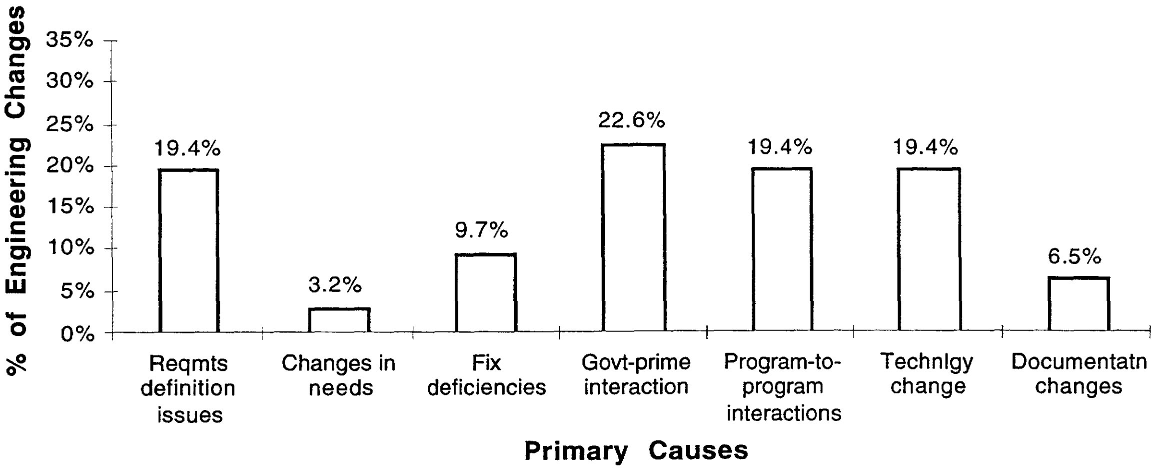
---

[88] One level below MSS.
[89] The highest level for that associate contractor.

Program A could shift the design baselines of Program B. In this case, Program B would then introduce engineering changes to accommodate the shifts in design baselines.

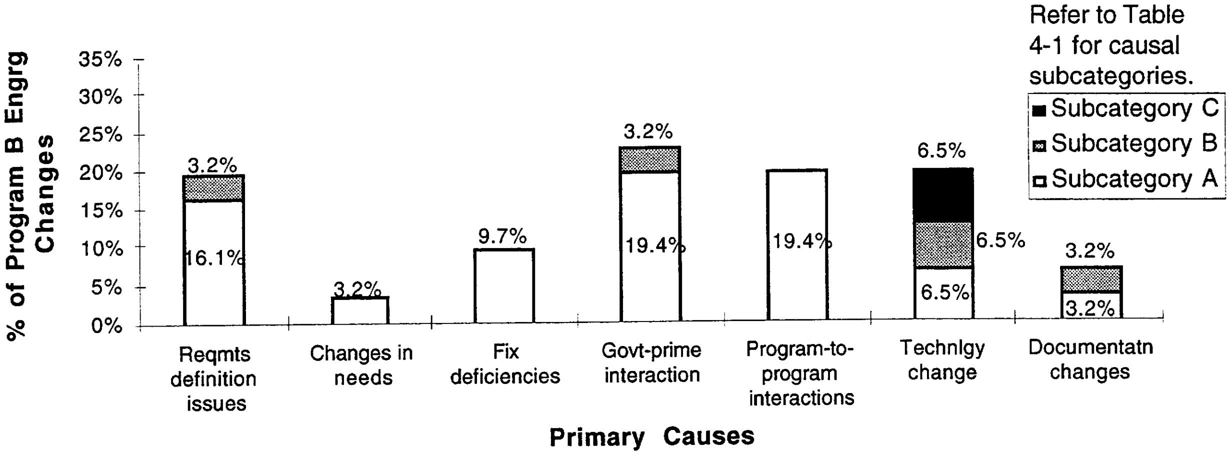
4.3.4 Patterns of Engineering Changes

Figure 4-5 shows the distribution of engineering changes in Program B in terms of their primary causes. It is clear that most of the engineering changes in Program B were due primarily to requirements definition issues, government-prime interactions, program-program interactions, and technological changes. Figure 4-6 shows the breakdown of the primary causes into the causal subcategories given in Table 4-1.



Total number of Program B engineering changes: 31.

Figure 4-5: Primary causes of engineering changes in Program B



Total number of Program B engineering changes: 31.

Figure 4-6: Breakdown of primary causes of engineering changes in Program B

Just as in Program A, the combination of dominant causes of engineering changes in Program B can be explained in terms of the program's characteristics. First, despite frequent contacts among the two associate contractors and the customer during full-scale development, engineering changes due primarily to requirements definition issues remained. In particular, some of these engineering changes involved the need to clarify a disagreement between the parties on how to measure two fundamental performance parameters of the all-new Subsystem B1 computer. In addition, there were numerous rewrites on Subsystem B1 test procedures. Second, 19.4% of Program B's engineering changes were due to the customer-mandated associate contractor arrangement. Since some changes affected specifications for which both contractors were responsible, both contractors had to introduce the necessary engineering changes. In a single-prime arrangement, normally only one engineering change would be submitted for a particular change issue. Therefore, one of each pair of such engineering changes was the result of the associate contractor arrangement required by the customer. As shown in Figure 4-6, very few of the engineering changes in Program B were due primarily to surprises created by previous engineering changes (subcategory 1B in Table 4-1), or to overly stringent specifications (subcategory 4B in Table 4-1). Third, another 19.4% of the engineering changes in Program B were due primarily to changes in Program A (i.e., program-to-program interactions). Finally, since Program B was basically a technology development program, it may not be surprising that the technological changes, in the aggregate, represented a significant cause. According to Figure 4-6, technology-related engineering changes were made in equal proportions to take advantage of newer technology[90], to deal with diminished manufacturing sources[91], and to modify requirements to accept capability[92] achievable in a technology development program. These causal subcategories have been outlined as 7A, 7B, and 7C, respectively, in Table 4-1.

The less dominant causes should also be explained. The single engineering change due primarily to changes in needs, accounting for 3.2% of all engineering changes in Program B resulted from the need to relocate a piece of safety equipment so that operators of relatively small physical stature could reach it. This was considered a change in user need, since at the time the improvement kit for Subsystem B1 was originally developed, there were no operators of such small physical stature. However, by the time the improvement kit was installed and tested, there were operators with sufficiently small physical stature who could not reach the safety equipment. One of the engineering changes made to fix deficiencies was a software rewrite to remove a discovered safety hazard. The others were aimed at fixing a newly developed display that did not perform as expected. The solution was to use a different display that required significant redesign of its cabinet and cooling. Finally, documentation changes were those made to ensure that design documentation were in order, and to consolidate two flight tests into one.

4.3.5 Discussion

Several observations about the Program B case study should be made. These include early supplier integration into product development, the use of associate contractor arrangement in full-scale development, and the dependence on Programs A. These observations are in addition to the one which indicated that Program B's combination of dominant causes of engineering changes depended on characteristics of Program B.

---

[90] An example would be the weight-saving removal of a computer cabinet whose function was taken over by parts of the new computer.

[91] For example, the engineering change allowing the use of the newer version of an instrument attached to the Subsystem B operator's console.

[92] The capability increase in Program B required some unprecedented technologies, where "no one really knew the answer." There is a point beyond which increased capability no longer justified the required effort to getting it.

Despite the early involvement of the key supplier responsible for Subsystem B1 in the product development process, requirements definition issues remained as one of the dominant causes of engineering changes in Program B. The engineering changes due primarily to requirements definition issues pertained to redefining performance measures for the new Subsystem B1 computer, and rewriting software test requirements.

The use of the associate contractor arrangement also warrants some discussion. On the level most related to engineering changes, the use of the associate contractor arrangement during full-scale development would necessitate two engineering changes to address one change issue if it affected both associate contractors. Government and contractor personnel also pointed out that in the development of a complex product such as Subsystem B1, the use of the associate contractor arrangement increased the possibility of specifications managed by the contractors going out of alignment. A special note about the associate contractor relationship pertains to the applicability of the aforementioned observations to other programs. The observations do not in any way address the merits of developmental programs in which multiple prime contractors develop equivalent but competing products with the understanding that there will be an eventual downselect to one prime contractor.

Finally, the observation that there were many engineering changes in Program B due to its dependence on the progress of Program A should not imply that such dependence was either good or bad. The data simply indicated that when programs closely follow one another, in the sense that Program B had to follow Program A because both programs involved the same fleet of aircraft, there could be many engineering changes on the follower program to incorporate relevant engineering changes from the predecessor program.

4.4 Program C

4.4.1 Purpose and Scope

The purpose of Program C was to provide a new user community with capabilities similar to those provided by Program A's aircraft prior to most of the upgrades introduced by Program A. Program C was a production program with some up-front development effort to ensure smooth integration of electronics mission subsystems into the aircraft. The user community would receive the overall system that included the airframe, the electronics mission subsystems, training facilities/equipment, and ground-based mission support facilities/equipment. Timely delivery (i.e., schedule) was a priority on this program.

The program can be considered unprecedented for a number of reasons. First, the scale and capabilities of the system would significantly enhance the capabilities of the new user community. Second, the development and production of the mission aircraft represented a large step for the prime contractor, because while the airframe and mission subsystems had already existed separately, their exact integration into the mission aircraft posed an entirely new challenge. Finally, the program adopted two new management practices: Clear Accountability in Design (CAID), and integrated product and process development(IPPD) using integrated product teams (IPTs). These two practices were also unprecedented in that they were used from the beginning of Program C, while only IPTs have been used during the production phases of Programs A and B.

4.4.2 Top-Level Description of Products

The Program C case-study included all aspects of the program except for the modification of the airframe in preparation for the integration of electronics mission subsystems. The portions of the program that fly away - the airframe plus electronics mission subsystems - would perform missions identical to those performed by the fleet of aircraft in Programs A and B. The mission subsystems were similar to those that had not yet received Programs A and B upgrades. Another portion of Program C included training and support facilities because the mission subsystems require trained operators, and the missions themselves need extensive preflight preparation. Of all three case-study programs, Program C was the most comprehensive in that it provided aircraft, mission subsystems, and training/support equipment.

The overall system was improved in two different ways under Program C. First, the requirements regarding training and ground support facilities and equipment were definitized and accommodated using engineering changes along the way during the program. Second, some improvements based on mature technologies from another program under the same System Program Office were selected and incorporated into Program C subsystems via engineering changes.

4.4.3 Product Development Process and Issues

This section highlights a number of product development issues in Program C. They include the use of CAID, the use of IPTs, and supplier integration into product development.

One of the new program management practices implemented in Program C was Clear Accountability in Design (CAID). Under CAID, the single prime contractor of Program C was responsible for developing and meeting lower level specifications (anything lower than mission system specification). The customer controlled only system specification (SS) and mission system specification (MSS) during development[93], and would take control of the lower level specifications at a later date, such as after Functional Configuration Audit (FCA)/Physical Configuration Audit (PCA)[94]. This means that engineering changes not affecting at least MSS could be implemented by the prime contractor without program office approval. Therefore, engineering changes in Program C affecting only lower level specifications were not directly observable by the customer, while in Programs A and B, which did not implement CAID, such changes could in fact be directly observed. Consequently, normalization according to levels of specifications affected by engineering changes would be necessary when comparing engineering change data across all three programs.

The prime contractor for Program C also employed integrated product teams (IPTs) for each subsystem to be integrated into the aircraft from the beginning of the program. According to interview data, use of IPTs enhanced the prime contractor's ability to properly define requirements early in the program by ensuring that the requirements of the IPTs were properly accounted for through systems engineering. Having properly defined the requirements included not only knowing what had to be firmly defined early, but also what could be deferred until later.

---

[93] For a comparison among programs in this regard, refer to Table 4-2.

[94] Program C FCA/PCA had not occurred when the data collection effort for this research ended.

4.4.4 Patterns of Engineering Changes

Figure 4-7 shows the relative importance of the primary causes of engineering changes on Program C. The decomposition of the data into causal subcategories is shown in Figure 4-8. It is apparent from Figure 4-7 that a high percentage of Program C engineering changes was due primarily to changes in needs, changes in technology, and the need to align documentation.

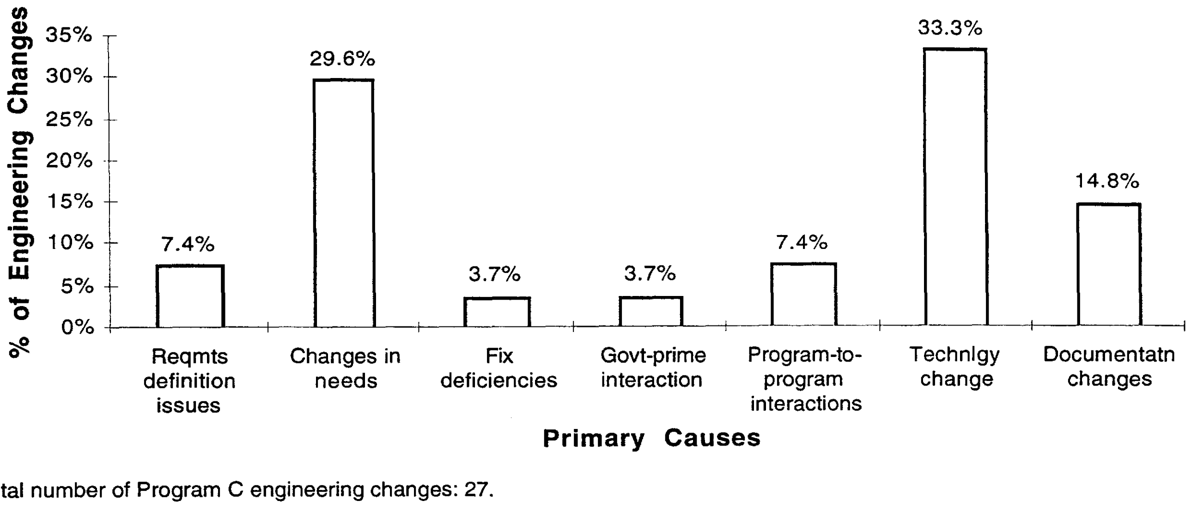


Figure 4-7: Primary causes of engineering changes in Program C

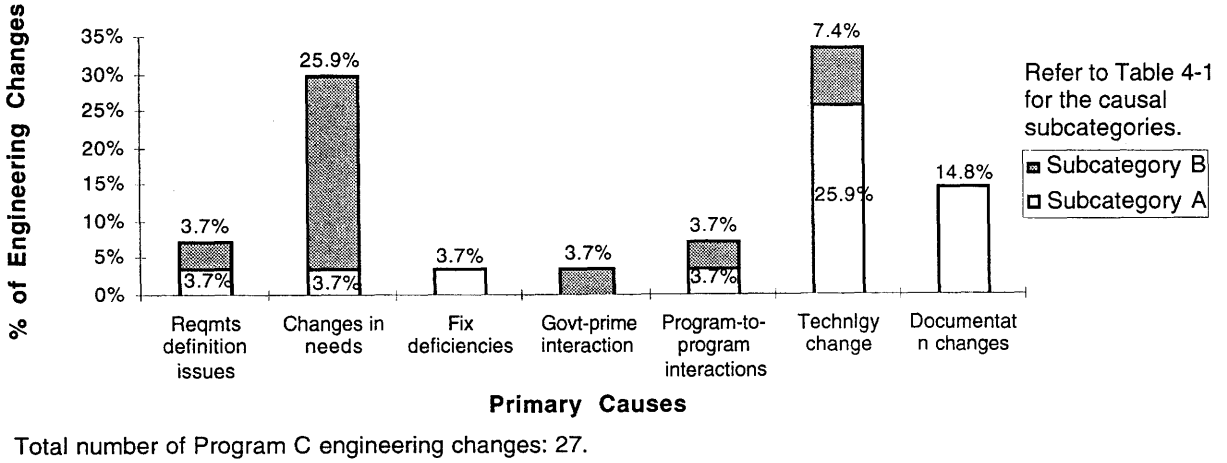


Figure 4-8: Breakdown of primary causes of engineering changes in Program C

Most of the engineering changes in Program C that were due primarily to changes in needs, resulting from the definitization of the user community's requirements for training and support facilities/equipment (subcategory 2b in Table 4-1). The design of the overall system was changed by the addition of these facilities and equipment. The single engineering change due primarily to added requirement (subcategory 2a in Table 4-1) was one in which the customer added certain flight tests to learn more about the possible interference between one electronics mission subsystem and parts of the aircraft on which the subsystem was installed.

The engineering changes related to technological changes were implemented to take advantage of more recent technological developments. Most of these newer technologies were adopted from another program under the same SPO. A number of technology-related engineering changes were introduced to make use of available flight test assets to replace those that were difficult to obtain due to obsolescence.

Finally, the need to align documentation was another important cause of engineering changes in Program C. Since the fleet of mission aircraft being acquired under Program C was unprecedented, some engineering estimates were based on data from existing, similar aircraft. After the Program C mission aircraft was produced, these estimates in specification documents were replaced with data based on the actual Program C mission aircraft.

It is noted here that requirements definition issues turned out not to be a dominant cause of engineering changes in Program C, accounting for only two engineering changes. One was made to address a requirement that had remained unfulfilled since the beginning of the program, while the other was made to correct documentation errors introduced, but not accounted for, when two prior engineering changes had been implemented.

Additional engineering changes in Program C should also be explained. For instance, a deficiency in a navigation subsystem was corrected by implementing the single engineering change to fix the deficiency. Another engineering change was done to replace a customer-imposed verification procedure for a certain piece of support equipment with one that was less rigorous. This was accomplished because the support equipment had already been verified for use with another aircraft. The engineering changes related to program-to-program interactions resulted from a baseline shift in a Program C subsystem that was previously developed under another program, and also from the realignment of some flight tests.

4.4.5 Discussion

The previous discussion in this chapter led to one general observation about the causes of engineering changes in Program C. The combination of dominant causes of engineering changes in Program C depended on the characteristics of Program C.

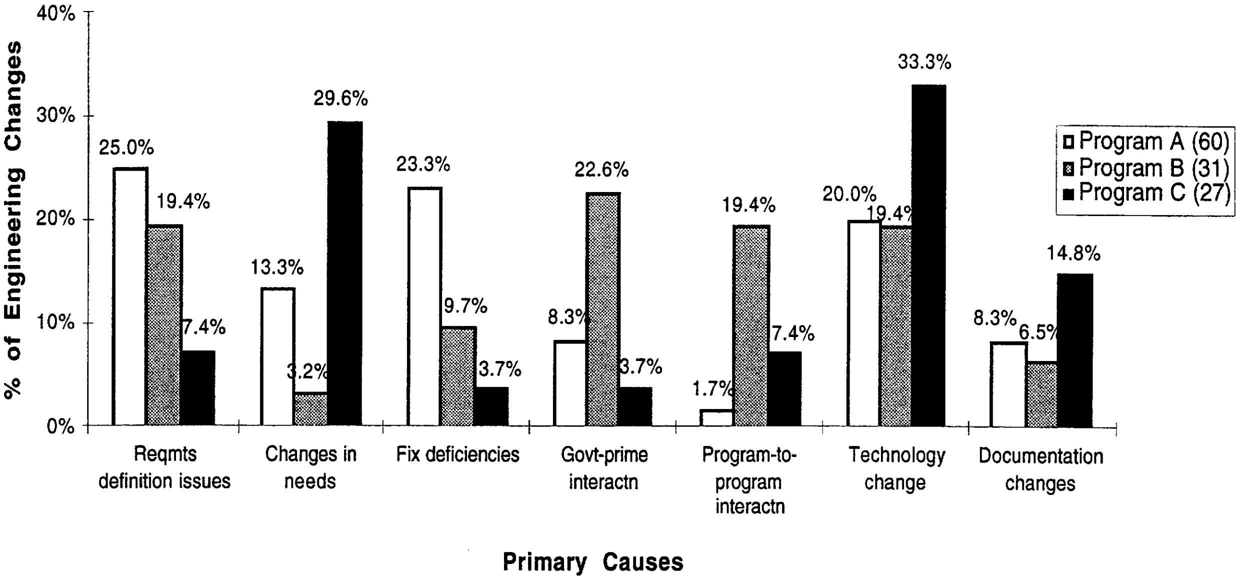
A main point that should also be underscored from this case study is that the use of IPTs helped Program C to define many of its requirements early in the program. This provided the opportunity later to readily improve the overall system by assessing and accommodating changes in user needs (e.g. those pertaining to training and support facilities/equipment) as well as changes in technology. One program representative has indicated that these engineering changes have been incorporated quickly because they were innocuous and that the newer technologies involved were mature and of low risk. On the other hand, integration problems had also been encountered, as pointed out during another interview. The interview data suggested that mature technologies should not be automatically consider as being low risk.

4.5 Primary Causes of Engineering Changes: Data Aggregation & Normalization

A special note about the absence of "funding reduction after program start" as a primary cause of engineering changes is provided here before further discussion of the results. This possible cause is not explicitly shown in any of the figures in this thesis since none of the engineering changes in the database could be linked to any funding reduction after program start. This does not mean, however, that "funding reduction after program start" cannot be a cause of engineering changes in other programs.

4.5.1 Combinations of Dominant Causes of Engineering Changes

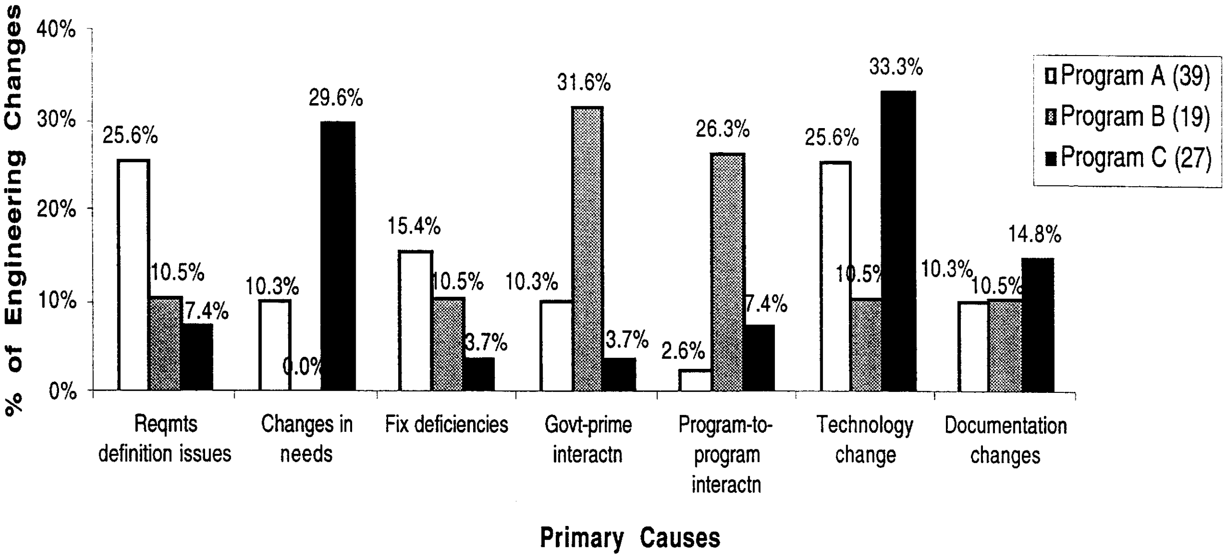
Figure 4-9 shows the primary causes of engineering changes in all three programs. The combination of dominant causes in each program (i.e., three tallest bars in the figure for each program) is different across the three programs. The dependence of the difference on program characteristics had been discussed in Sections 4.2, 4.3, and 4.4.



Across 3 programs, based on all 118 engineering changes in database.

Figure 4-9: Primary causes of engineering changes in each of the three programs

The data normalization processes warrant some discussion. As shown in Figure 4-10, the qualitative comparison across the three programs for each primary cause remained largely unchanged when the data were normalized by removing from Program A and B data the engineering changes that affected only specifications lower than and not including the MSS level in order to make consistent comparisons with the data from Program C. In addition, the engineering change data were also normalized using data for only 3.5 years since the inception of each program. This duration was chosen based on the shortest interval of data availability. Since all three programs were at approximately the same phase when the research began, this latter normalization was not considered as compelling as the former. Nevertheless, the results are given in Appendix D. In effect, this latter normalization reduced the relative importance of one primary cause (i.e., fix deficiencies), and increased the importance of another primary (i.e. documentation changes) in Program A. Furthermore, it also reduced the relative importance of one primary cause in Program B (i.e., changes in technology).

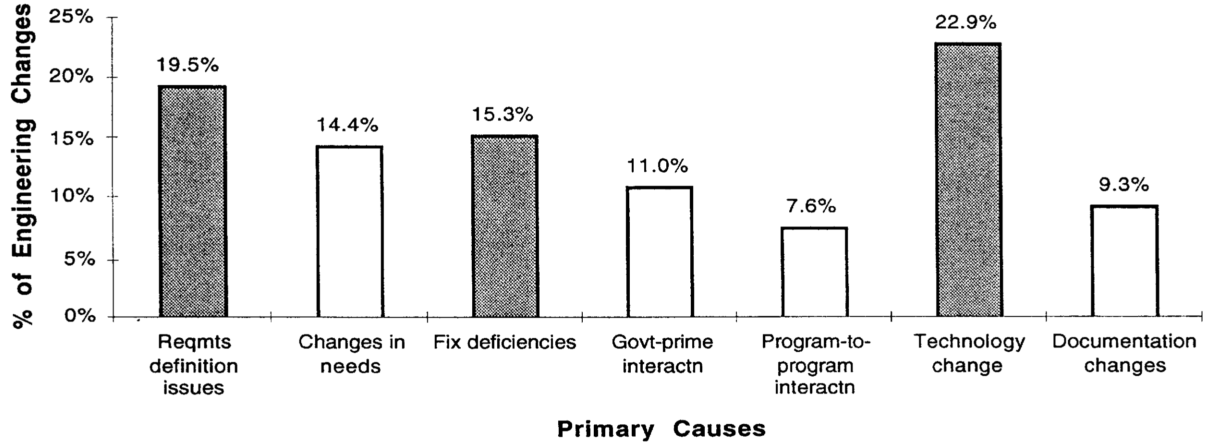


Across 3 programs, based on 85 engineering changes affecting SS and/or MSS only.

Figure 4-10: Specification-normalized primary causes of engineering changes on each of the three case-study programs

4.5.2 Dominant Causes of Engineering Changes Across 3 Programs

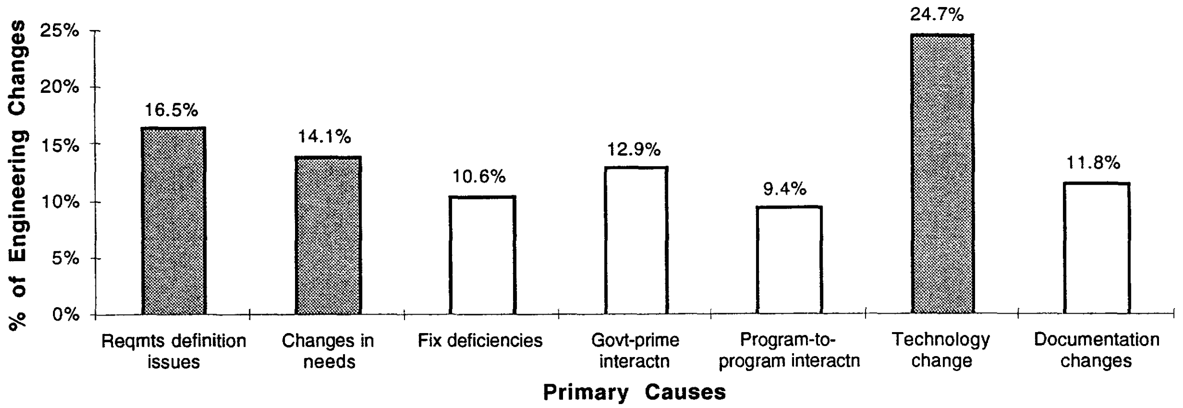
One more aggregation of the data on the causes of engineering changes across all three programs identifies the dominant causes of engineering changes across the three programs. The results are shown in Figure 4-11.



Across 3 programs, based on all 118 engineering changes in database.

Figure 4-11: Dominant causes of engineering changes across three programs

As shown in Figure 4-11, requirements definition issues, the need to fix deficiencies, and technological changes were the top three dominant causes of engineering changes across Programs A, B, and C. Changes in needs as another dominant cause was added as a result of normalization of the comprehensive data by removing engineering changes that did not affect system specification (SS) and/or mission system specification (MSS). The specification-normalized result is shown in Figure 4-12.



Across 3 programs, based on 85 engineering changes affecting SS &/or MSS only.

Figure 4-12: Specification-normalized dominant causes of engineering changes across 3 programs

A comparison of Figure 4-12 and Figure 4-11 shows that the need to fix deficiencies no longer appears as one of the top three dominant causes. This was largely due to the fact that a large number of the more recent engineering changes in Programs A and B did not impact the system specification and/or the mission system specification. Instead, the data normalization identified changes in needs as one of the three dominant causes across the three programs. Thus, four dominant causes of engineering changes are identified (i.e., top three from Figure 4-12, and the need to fix deficiencies from Figure 4-11).

4.6 Summary of Findings

This chapter has identified several findings based on the case studies. These findings provided some answers to the key questions stated at the beginning of Chapter 3.

4.6.1 Causes of Engineering Changes

The research has identified four dominant causes of engineering changes (three using the specification-normalized data, one added based on the comprehensive data set): requirements definition issues, changes in needs, changes in technology, and the need to fix deficiencies. However, the case studies and their engineering change data also demonstrated that the characteristics of each program largely shaped the combination of dominant causes of engineering changes in each program.

4.6.2 Use of Off-the-Shelf Subsystems

The Program A case study provided a lesson-learned about the use of off-the-shelf subsystems. Subsystem A1 was an advanced subsystem developed and produced for another branch of the armed services. In this case, the assumption that it could be easily adopted, with little modification, for operations in a significantly different environment led to substantial redesigns of an off-the-shelf item. The implication is that the use of an off-the-shelf subsystem, without a firm understanding of the operational environment that the subsystem must endure, may lead to substantial redesigns, thereby eroding the possible benefits of using the off-the-shelf subsystem in the first place.

4.6.3 Engineering Changes & the Integration of Key Suppliers into Product Development

The data available from Programs A and B indicate that early involvement of key suppliers in product development, by itself, would be insufficient to reduce the percentage of engineering changes that were primarily due to requirements definition issues. This observation will be further elaborated upon in Chapter 5.

4.6.4 Engineering Changes and the Use of IPTs

The use of IPTs by the prime contractor in Program C helped to clarify requirements as much early in that program. The relative lack of engineering changes that were due primarily to requirements definition issues gave rise to opportunities to quickly and effectively assess and accommodate newly definitized user needs and to introduce incremental improvements in technology. Figure 4-13 summarizes these results. Figure 4-14 shows that these results largely held when the specification-based normalization was applied to the data shown in Figure 4-13.

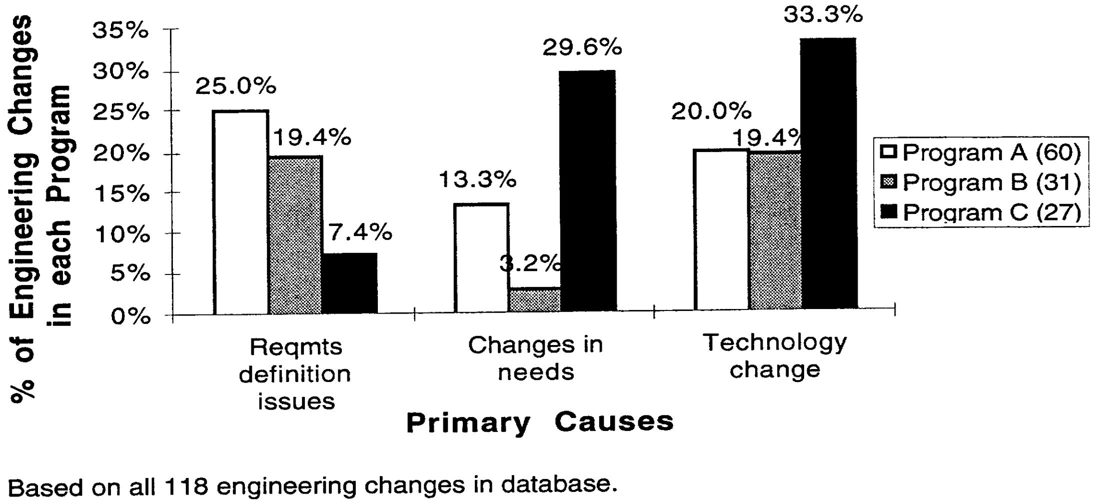


Figure 4-13: Engineering changes and the use of IPTs

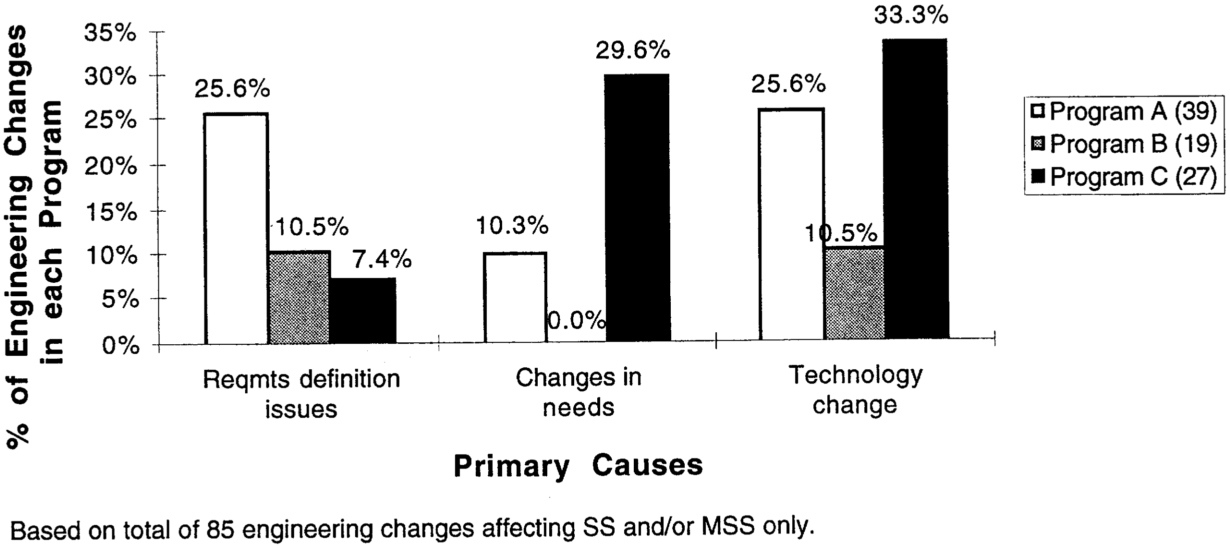


Figure 4-14: Specification-based normalization of data relating engineering changes and use of IPTs

4.7 Chapter Summary

This chapter has begun to show findings resulting from the case studies based on the three programs. It described the programs, and showed the relationship between program characteristics and the causes of engineering changes on these programs. In addition, this chapter identified four dominant causes of engineering changes across the three programs, and presented some lessons learned about defense aerospace product development.

The next chapter will continue to discuss the findings of the research. It will focus on the impacts of engineering changes.

5. Impacts of Engineering Changes

This chapter continues the discussion of engineering changes by examining their impacts. The goals of the research described here are to understand the nature of these impacts and provide some observations about their possible implications for the defense aerospace product development process. The data presented are the result of translating descriptive data into quantitative codes using the framework presented in Table 5-1, which is repeated here from Section 3.4.1 for the convenience of the reader. The reader is also encouraged to refer to Section 3.4.1 for detailed discussion of the impact areas listed in Table 5-1.

1	**Near-term cost impact**
	• More cost with engineering change than without • Less cost with engineering change than without • Not impacted
2	**Program schedule**
	• Delayed • Advanced • Not impacted
3	**Product performance with respect to expectation**
	• Increase • Decrease • Met shifted expectation with engineering change • Met existing expectation with engineering change • Not impacted
4	**Primary impact on prime contractor's work**
	• Rework • New work • Less work • Not impacted
5	**Primary impact on supplier(s)' work**
	• Rework • New work • Less work • Not impacted
6	**Impact on other programs in SPO**
	• Yes • No
7	**Additional, unanticipated engineering changes over the same issue in the same program**
	• Yes • No

Table 5-1: Framework for categorizing impacts of engineering changes

Two cautionary remarks are appropriate at this time. First, the results provide qualitative aspects of impacts, rather than quantitative measures. Second, the data and results were limited in terms of their ability to answer detailed questions regarding the internal operations of the prime contractors and suppliers.

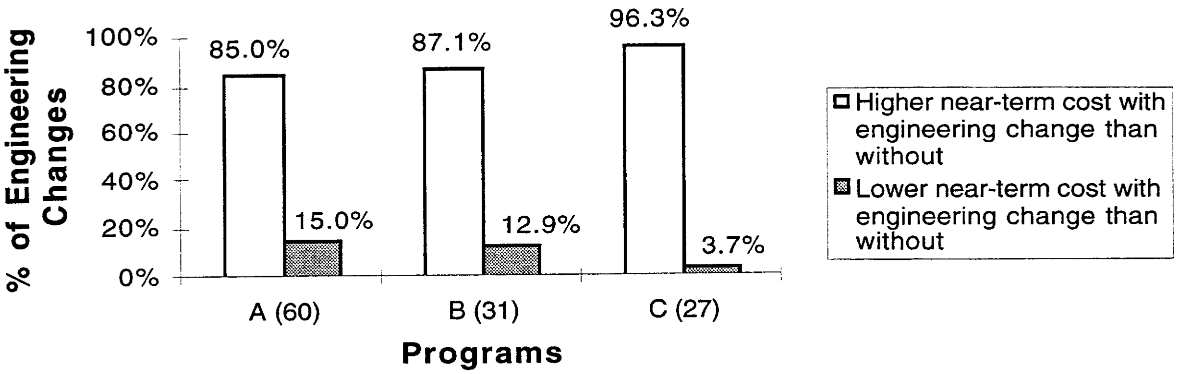
Flood and Carson[95] point out that two basic elements of complexity are "things and people." Cost, schedule, and product performance can be considered three "things" about the case-study programs. Section 5.1, 5.2, and 5.3 each deals with these "things" aspects of the programs. The various communities involved with the systems being acquired by the programs are the "people" aspects. Sections 5.4, 5.5, and 5.6 address the "people" aspects in terms of the impacts of engineering changes on the prime contractor(s), supplier(s), and other members of the acquisition community represented by other programs in the same System Program Office. Finally, Section 5.7 examines whether engineering changes in the three case-study programs led to surprises in the same programs, which had to be addressed by more engineering changes. This impact area arguably pertains to both "things" and "people". Section 5.8 highlights the major findings regarding the impacts of engineering changes, and Section 5.9 summarizes the chapter.

5.1 Near-term Cost Implications of Engineering Changes

Cost, in general, is one of the major "things" to consider in evaluating a defense acquisition program. In the research reported here, all engineering changes tended to either increase or decrease the near-term cost of the program. In other words, all engineering changes impacted near-term cost of the programs. Figure 5-1 shows the result.

---

[95] Flood, Robert L. and Ewart R. Carson. *Dealing with Complexity: An Introduction to the Theory and Application of Systems Science*, 2nd ed. New York, NY: Plenum Press, 1993, pp.24-25.



Based on all 118 engineering changes in database.

Figure 5-1: Near-term cost implications of engineering changes

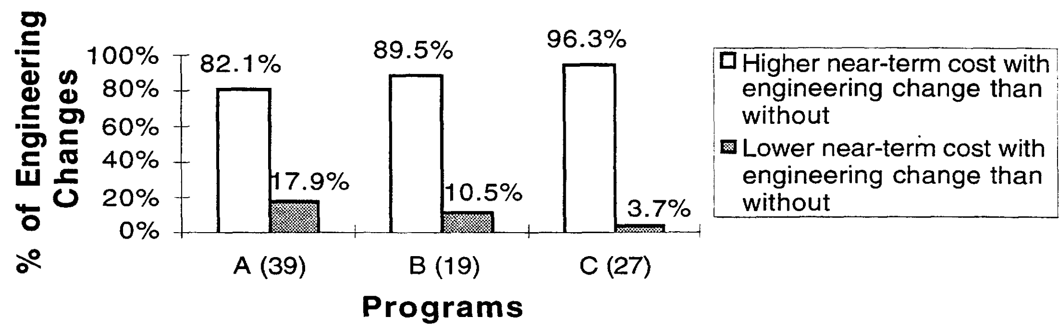
The left-hand-side bars in each cluster in Figure 5-1 show the percentages of engineering changes in each program that led to higher cost involved in the program, than would have been the case without the engineering changes. The near-term cost increases could mean additional cost to the customer, such as in the case of changing the design of the overall system by acquiring additional equipment. The near-term cost could also tend to be higher if a contractor must conduct a redesign in order to meet requirements. In the latter case, the near-term cost increases were not reported on the ECP submittals, but could be inferred from the descriptions documented in the submittals or in other descriptive materials related to such engineering changes.

The right-hand-side bar in each cluster in Figure 5-1 shows that some engineering changes on each program led to lower near-term cost involved in the program, than would have been the case without those engineering changes. Typically, these reductions resulted from modifications in requirements[96] to accept obtainable capabilities instead of redesigning to obtain further incremental increases in capabilities. The latter would mean higher near-term cost for certain parties involved in developing/producing the system. The reductions also represented a smaller number of engineering changes which served to remove overly stringent or redundant requirements. Otherwise, complying with these requirements would likely have made the product more expensive for the contractor to build.

---

[96] Engineering changes can either change the design/product, the documentation describing the design/product, or both the design/product and the documentation.

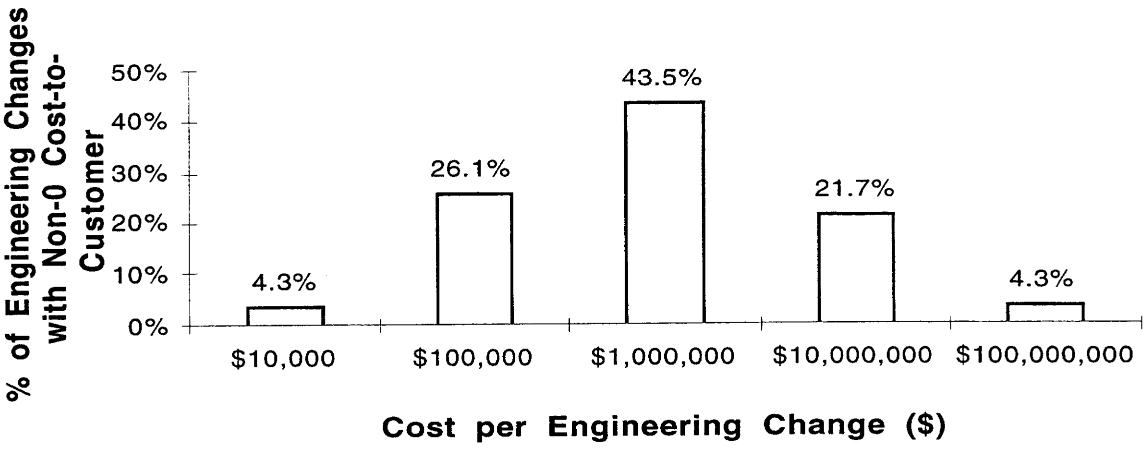
Two cautions about the preceding discussion should be given. First, readers should not necessarily conclude that because most engineering changes tend to make a program more expensive, that engineering changes are therefore necessarily undesirable. As noted before, capabilities can be increased at a cost and users may decide to accept the cost so as to realize the additional capability. Second, the results in Figure 5-1 also held when engineering changes affecting only lower-level specifications were removed from the data set, as shown in Figure 5-2.



Based on 85 engineering changes affecting SS and/or MSS only.

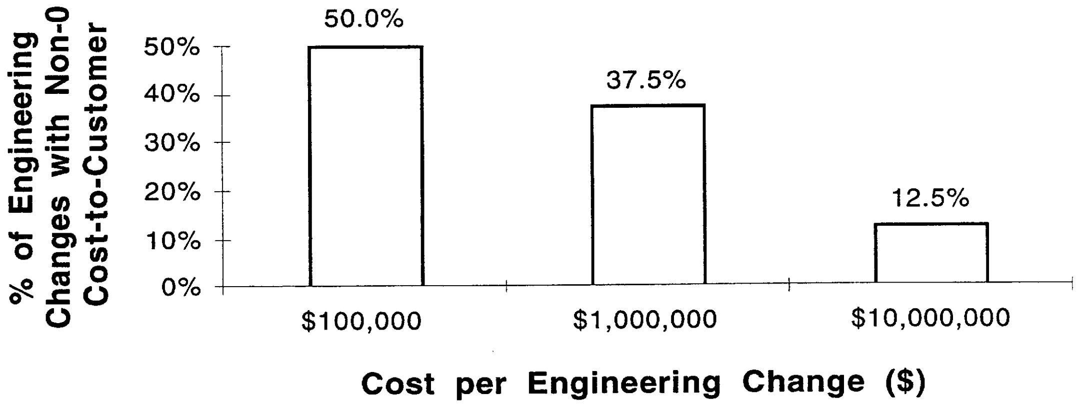
Figure 5-2: Specification-normalized near-term cost impacts of engineering changes

Some data from ECP submittals were available to indicate the orders of magnitude of additional customer expenses for having engineering changes made to the product's design. The orders of magnitude of dollar figures from Programs A, B, and C are shown in Figure 5-3, Figure 5-4, and Figure 5-5. Data from Programs A and C demonstrate roughly bell-shaped distributions of cost-to-customer of engineering changes, while those from Program B show a very roughly exponential distribution.



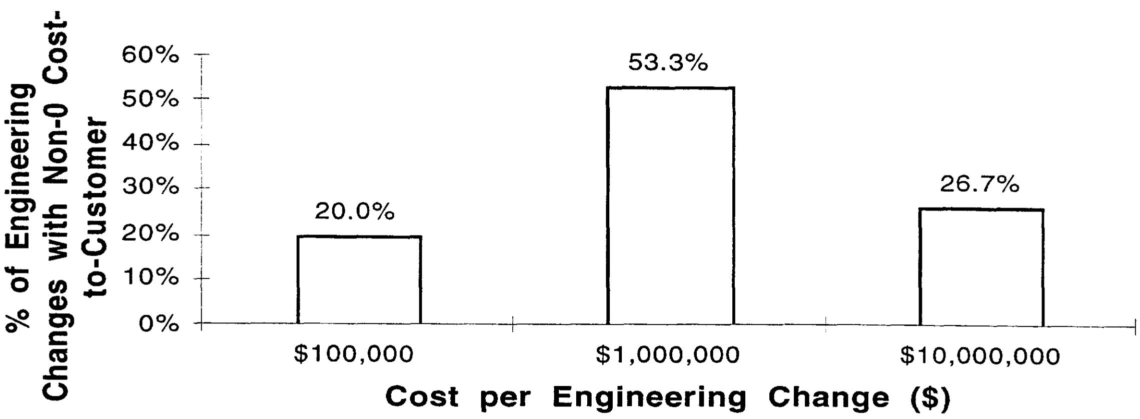
Note: 23 of 60 engineering changes had non-zero cost-to-customer.
Percentages are based on 23, not 60.

Figure 5-3: Program A cost-to-customer of engineering changes



Note: 16 of 31 engineering changes had non-zero cost-to-customer.
Percentages are based on 16, not 31.

Figure 5-4: Program B cost-to-customer of engineering changes

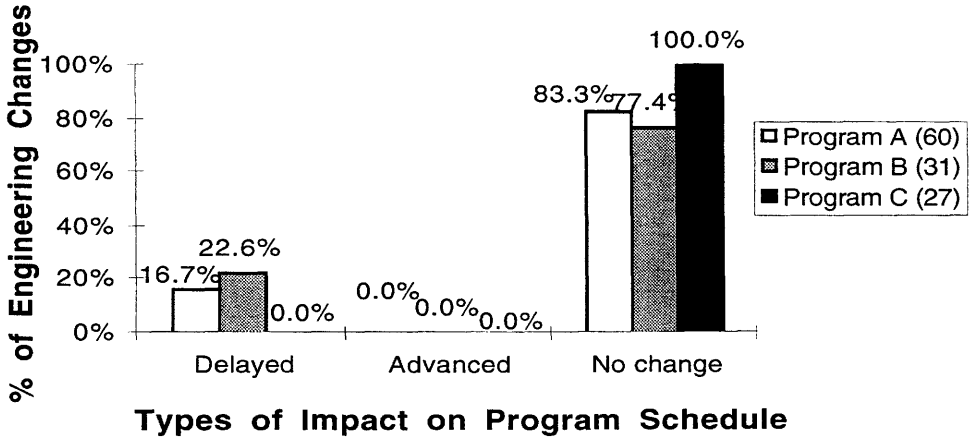


Note: 15 of 27 engineering changes had non-zero cost-to-customer.
Percentages are based on 15, not 27.

Figure 5-5: Program C cost-to-customer of engineering changes

5.2 Impacts of Engineering Changes on Program Schedule

Program schedule is another "thing" of concern on defense acquisition programs. Figure 5-6 shows the percentage of engineering changes on each program impacting or not impacting program schedule.



Based on all 118 engineering changes in database.

Figure 5-6: Impacts of engineering changes on program schedule

The most striking observation about the results in Figure 5-6 is that the vast majority of engineering changes did not impact program schedule. The result may not seem so striking when the existence of the configuration control process is considered. This process is used to evaluate the impacts, including the impact on program schedule, of each engineering change.

The second interesting observation is that no engineering change in the data set resulted in advancing the program schedule. One possible explanation is that the act of advancing the schedule may lead to increased cost for certain parties, such as the contractors. Indeed, changing the design in order to complete something faster would require studying the possible modifications to the design, making an Advance Change Study Notice (ACSN)[97] to the customer, and if the customer gives the go-ahead, conducting a full-scale study to propose the engineering change. Different communities, potentially including the users, program office, the prime contractor, and their suppliers, would be involved in this process[98]. These activities and interested parties represent potential sources of cost increase. In addition, every design change may carry some risk of something going wrong. Therefore, changing the design in order to achieve the goal of advancing the schedule may not achieve the goal in light of these potential problems. Program schedule is related to the much larger topic of acquisition cycle time of defense aerospace systems. More research and data about US defense acquisition cycle time in general can be found in the dissertation by McNutt[99].

It is useful to further explore the nature of engineering changes resulting in program schedule delays in Programs A and B. Engineering changes resulting in program schedule delays most often involved redesigns, as evidenced by both a review of the engineering change database maintained for this research, and interviews with customer and contractor personnel. In some cases the lengths of delay were identifiable from the documents, while in other cases they were not. The capabilities obtainable from these redesigns were critical enough to the customers that they decided to "buy", with some program schedule delay.

Another observation that can be made based on data presented in Figure 5-6 is that no engineering changes in Program C resulted in schedule delays for that program. Indeed, according

---

[97] An ACSN is like a preliminary ECP.

[98] The discussion is based on observations made while collecting data at the System Program Office.

[99] McNutt, Ross T. *Reducing DoD Product Development Time: The Role of the Schedule Development Process.* MIT Doctoral Dissertation. December 1998.

to data summarized in Table 4-2, Program C schedule did not slip at all. This result appears to be nearly impossible given that many engineering changes in Program C were due primarily to changes in user needs and technology.

Several factors are likely contributors to this result. First, program schedule was a priority in Program C. According to a program office representative, it was critical for the user community to have the capabilities in hand at the contracted time. Therefore, as an interview with one program office representative indicated, contractor and program office personnel worked extra hours over a significant period of time in order to prevent the program schedule from slipping. Second, the program's ability to properly define requirements[100] at an early stage in the development, with the aid of IPTs, also helped Program C achieve this result. Consequently, the program understood what could be added later and what could not. Finally, the use of mature technology was also suggested by the program office representative as a factor that helped to reduce schedule risk. The newer technologies added via engineering changes were proven, as opposed to developmental, technologies. Therefore, capabilities could be added incrementally with little schedule risk.

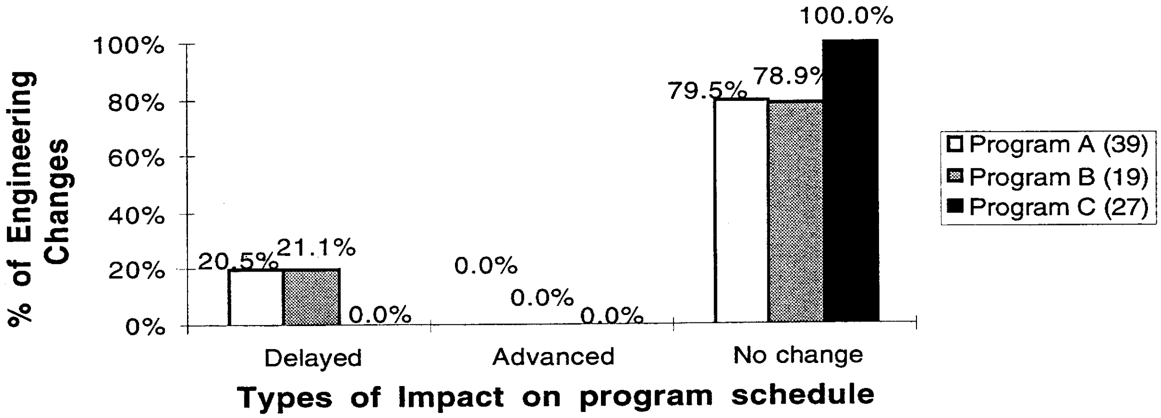
Some qualifications should be made with regard to the program schedule-related data. First, it should not be inferred that engineering changes are the only possible sources of program schedule delays. As personnel interviewed at the System Program Office (SPO) indicated, Contract Change Proposal (CCP) is another contract vehicle capable of allowing a program schedule slip. For example, one major program milestone in Program A was delayed using a CCP. CCPs were outside the scope of the data collected for this research. In addition, a System Program Office representative pointed out that flight test failure by electronic mission subsystems could also lead to program schedule delay. It was also pointed out by the SPO that Program B did not pass one major milestone test, and the program was set back by two years. Second, the relatively low percentages of engineering changes that led to program schedule delays should not necessarily lead to the conclusion that the magnitudes of the delays were small.

---

[100] Recall from Chapter 4 that only one engineering change in Program C was attributable to requirements definition issues.

Third, the results showing the majority of engineering changes did not delay program schedule do not imply that all tasks on the programs were completed on time.

The specification-normalized results of Figure 5-6 are shown in Figure 5-7. The major conclusions remain unchanged.



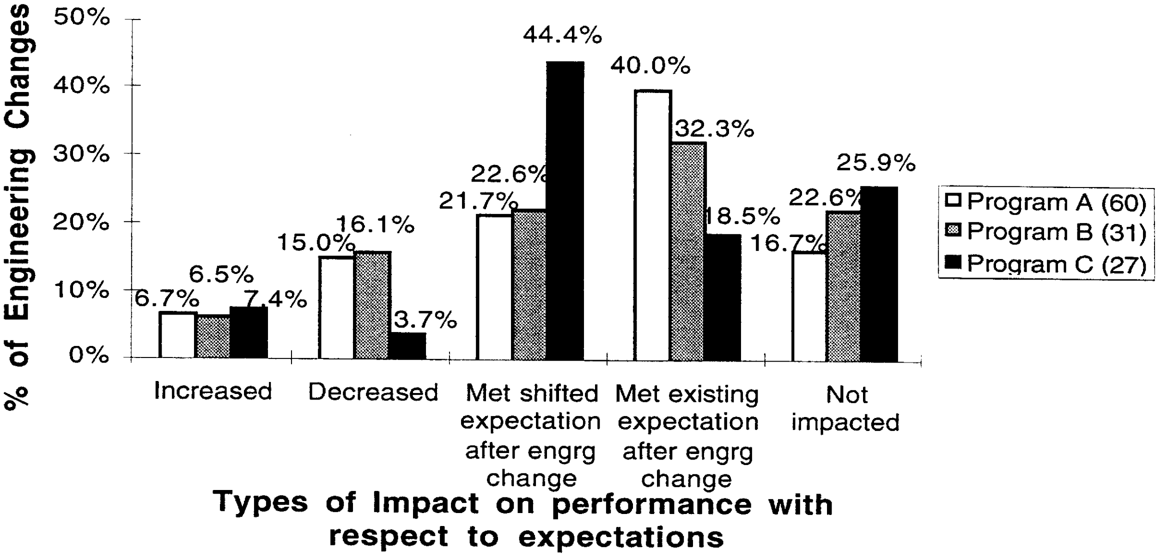
Based on 85 engineering changes affecting SS and/or MSS.

Figure 5-7: Specification-normalized impact of engineering changes on program schedule

5.3 Impacts of Engineering Changes on Product Performance with Respect to Expectations

Performance of a defense aerospace product is also one of the “things” of interest about a program. It was necessary to think of performance relative to some customer expectation. Otherwise, a qualitative judgement about its increase or decrease would be meaningless. For example, an upgrade program should not make the performance of an existing product worse than before the upgrade. Similarly, an unprecedented capability would always be a performance increase when compared to not having that capability at all. Figure 5-8 shows the impacts of engineering changes on product performance with respect to expectations.

A few remarks about the translation of relevant descriptive data into the results presented in Figure 5-8 are in order. An engineering change incorporating recently available technology into a product would be categorized as an engineering change that increased product performance beyond originally specified customer expectations if the descriptive data indicated that the customer did not actively seek out the technology. On the other hand, an engineering change modifying requirements to accept obtainable capabilities instead of continuing development would be an engineering change that decreased product performance below what was originally specified. An example of engineering changes done to meet shifted expectation would be one that was done to incorporate updated training simulators at the request of the customer. Furthermore, engineering changes done to fix deficiencies and effect redesigns would be considered those done to meet existing expectations. Finally, engineering changes inferred to not have impacted performance would include those made to align documentation.



Based on all 118 engineering changes in database.

Figure 5-8: Impacts of engineering changes on product performance with respect to expectations

The lowest cluster of bars in Figure 5-8 was the one representing engineering changes having the impact of delighting the customer by increasing product performance beyond expectations. A surprising aspect of the result is that the three programs appear to be relatively even in terms of delighting the customer, given that it would have been more difficult for Programs A and B to do so since they had more substantial developmental content than Program C had.

Also, Program C had a comparatively smaller proportion of engineering changes done to modify requirements to accept obtainable performance. One possible explanation is that Program C's relatively low developmental content[101] gave it fewer unknowns to begin with. It could also be inferred that the use of IPTs contributed to Program C's ability to understand more unknowns earlier, thereby reducing the need to lower requirements later in the program.

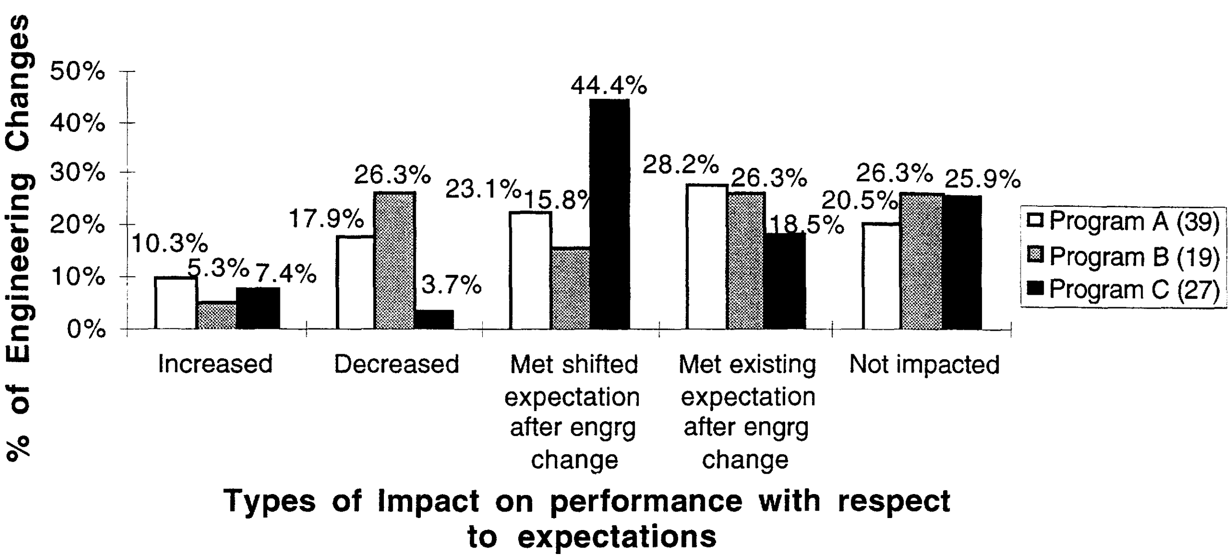
Figure 5-8 shows that more than 50% of engineering changes on each program were made to enable products to meet the customers' shifted and original expectations. Focusing on the cluster of bars representing engineering changes done to meet shifted expectations, it could be argued that understanding requirements early and having a "simpler" problem allowed Program C to make relatively fewer engineering changes in meeting original expectations and to focus more directly on accommodating shifted expectations.

Program C also had higher proportions of its engineering changes not impacting performance than the other two programs had. This was consistent with the observation in Chapter 4 that documentation changes represented one of the dominant causes of engineering changes in Program C.

Figure 5-9 provides a specification-normalized version of Figure 5-8. A comparison between Figure 5-8 and Figure 5-9 shows that the results in Figure 5-8 are sensitive to the specification-based normalization. For example, the normalized results show that fewer than 50% of engineering changes in Program B were made to meet expectations by meeting shifted and original expectations. This is because relatively many such engineering changes on Program B only impacted specifications lower than the mission system specification (MSS), and were thus removed by the normalization procedure. In addition, the normalization also increased the relative importance of engineering changes in Programs A and B that did not impact performance. Hence, Program C no longer has the highest proportion of engineering changes that had not impacted product performance.

---

[101] Most of the developmental work on Program C pertained to the integration of separate, existing products into an unprecedented whole.

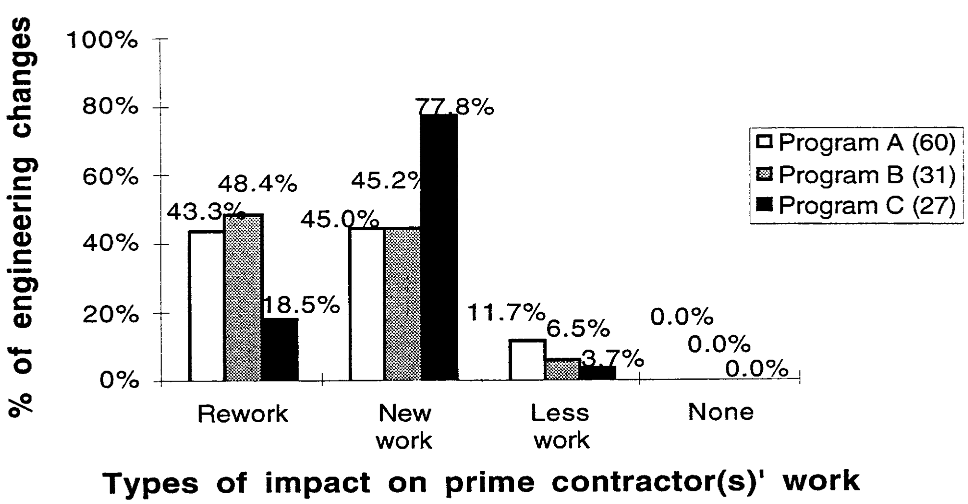


Based on 85 engineering changes affecting SS and/or MSS only.

Figure 5-9: Specification-normalized impacts of engineering changes on product performance with respect to expectations

5.4 Impacts of Engineering Changes on Prime Contractor(s)' Work

This impact area focuses more on the "people" aspects of complexity than previous impact areas did. Results represented by each cluster of bars in Figure 5-10 are explained and are related to program characteristics. An immediate observation is that all engineering changes on the three programs impacted what the prime contractor must do after the approval of the engineering change.



Based on all 118 engineering changes in database.

Figure 5-10: Impacts of engineering changes on prime contractor(s)' work

"Rework" occurred when something had to be done to repeat a task that was not done correctly the first time. Examples of rework for prime contractors include documentation corrections, repairs of existing products, and even significant redesigns traceable to requirements definition issues. The prime contractor of Program C had the least rework compared to those of Programs A and B. Properly defined requirements in the early phases of the program, aided by the use of IPTs, led to this result. Based on a close examination of the descriptions of engineering changes conducted as a part of this research, it was estimated that had IPTs been used during the development phases of Programs A and B, their percentages of engineering changes in the "rework" cluster could have been potentially reduced by 11.6 and 9.7[102] percentage points, respectively.

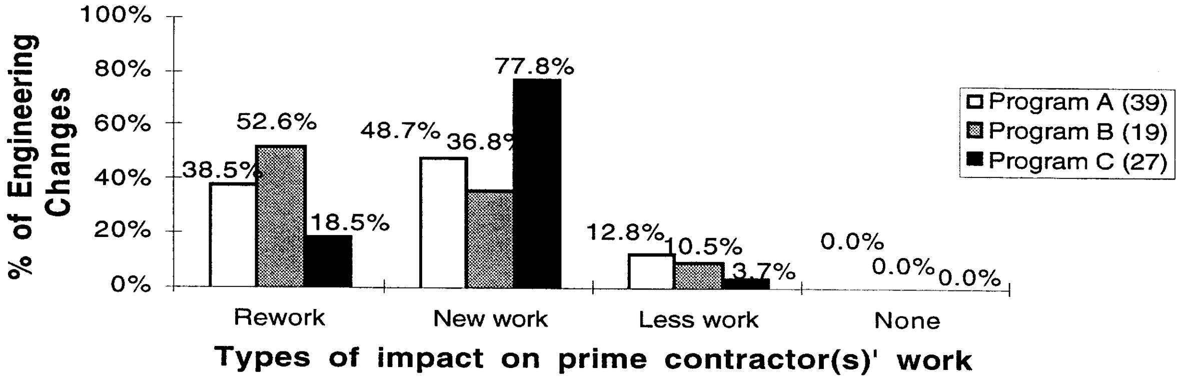
"New work" for the prime contractors involved tasks accomplished to adopt improved technologies and address evolving user needs. Engineering Changes in Program C led to relatively more new work for the prime contractor than did those in Programs A and B, because of numerous engineering changes in Program C to accommodate evolving user needs and technology.

---

[102] These engineering changes included some of those that were due primarily to requirements definition issues, and had potential to be avoided had functioning IPTs been in place. This observations is inferred from ECP descriptive data and interview results.

Finally, the lowest and non-zero cluster of bars in Figure 5-10 is that representing "less work" for the prime contractors. These engineering changes allowed the prime contractors to do less work than they otherwise would have performed without the engineering changes. An example would be an engineering change made to lower product performance requirements. By approving such an engineering change, the customer basically agrees to accept obtainable performance from the products of the program, which usually mean that the prime contractor can do less developmental work on that product.

Figure 5-11 below represents the specification-normalized version of Figure 5-10. The comparative relationships between engineering changes within each cluster remain largely the same as those in Figure 5-10. Programs A and B engineering changes in the "rework" cluster might have been reduced by 15.4 and 10.5 percentage points, respectively, had IPTs been used during development[103].



Based on 85 engineering changes affecting SS and/or MSS only.

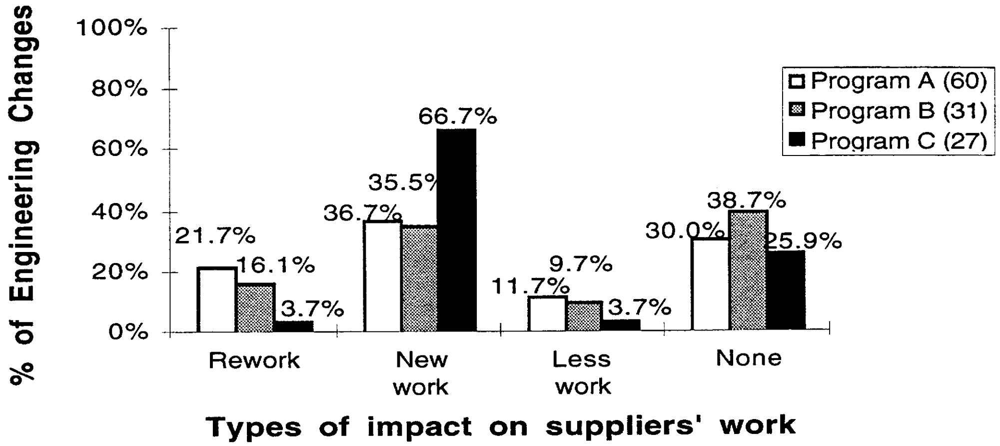
Figure 5-11: Specification-normalized impacts of engineering changes on prime contractor(s)' work

---

[103] This estimate pertains to those engineering changes that were due primarily to requirements definition issues, which had the potential to be avoided had IPTs been in place and functioning, as inferred from ECP descriptive data and interview results. These engineering changes refer to those impacting SS and/or MSS only.

5.5 Impacts of Engineering Changes on Supplier(s)' Work

This impact area is similar to the one regarding the impact of engineering changes on prime contractor's work. However, a difference between the results of these two impact areas, that can be immediately identified from Figure 5-12, is that data indicated that some engineering changes in the three programs did not impact suppliers.



Based on all 118 engineering changes in database.

Figure 5-12: Impacts of engineering changes on supplier(s)' work

Descriptive data about the engineering changes, supported by interview data, indicate that some suppliers to the prime contractors of Programs A and B may have been able to avoid some "rework" had IPTs been used to enable the prime contractors to better understand the capabilities and limitations of these suppliers. Recall from Chapter 4 that key suppliers were involved early in Programs A and B. Had IPTs been utilized, engineering changes in Programs A and B leading to rework by suppliers might have been reduced by 13.3 and 9.7[104] percentage points, respectively.

"New work" means new responsibilities for the suppliers. For example, when engineering changes called for the purchase of updated training equipment, the supplier of the

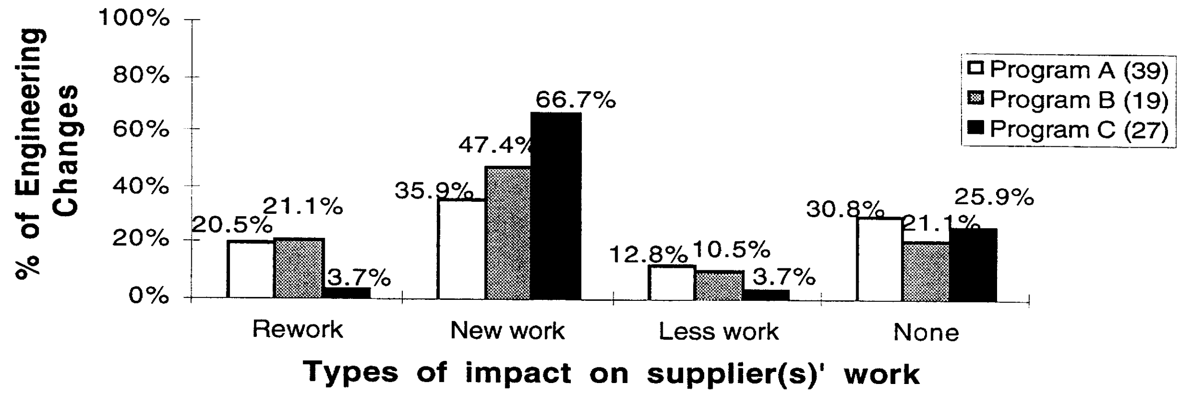
---

[104] These engineering changes included some of those that were due primarily to requirements definition issues, and could potentially have been avoided had functioning IPTs been in place. This observation is inferred from ECP descriptive data and interview results.

training equipment would respond to the previously unknown purchase by providing the updated training equipment as required by the engineering change.

Finally, a relatively small proportion of engineering changes led to "less work" for the suppliers. This means that only a small proportion of engineering changes allowed suppliers to reduce certain previously required tasks.

Figure 5-13 shows that specification-based normalization slightly altered the comparative relationships between bars in the "rework" and "none" clusters. However, the interpretations of the results based on program characteristics remain the same. The engineering changes in Programs A and B that led to rework by subcontractors (suppliers) might have been reduced by 12.8 and 10.5 percentage points, respectively, had IPTs been used[105].



Based on 85 engineering changes affecting SS and/or MSS only.

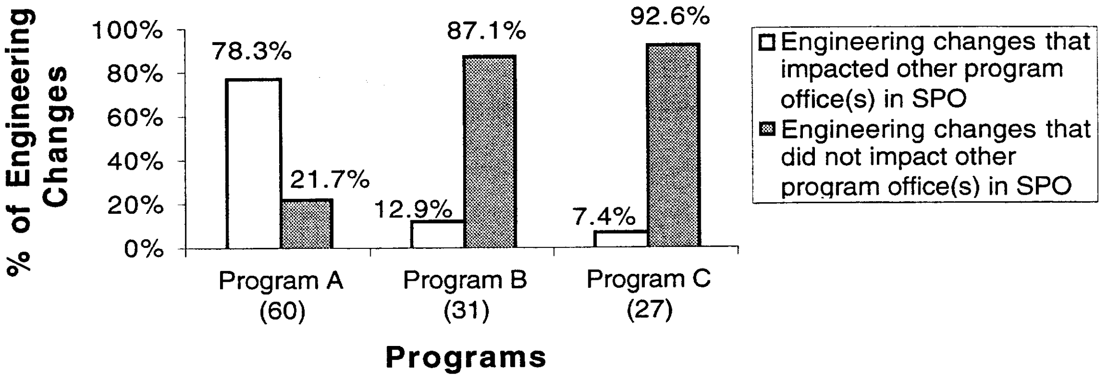
Figure 5-13: Specification-normalized impacts of engineering changes on supplier(s)' work

---

[105] These engineering changes were those due primarily to requirements definition issues, and had the potential to be avoided had IPTs been in place and functioning. The observation is inferred from ECP descriptive data and interview results. These engineering changes selected from those impacting SS and/or MSS only.

5.6 Impacts of Engineering Changes on Other Programs under the Same SPO

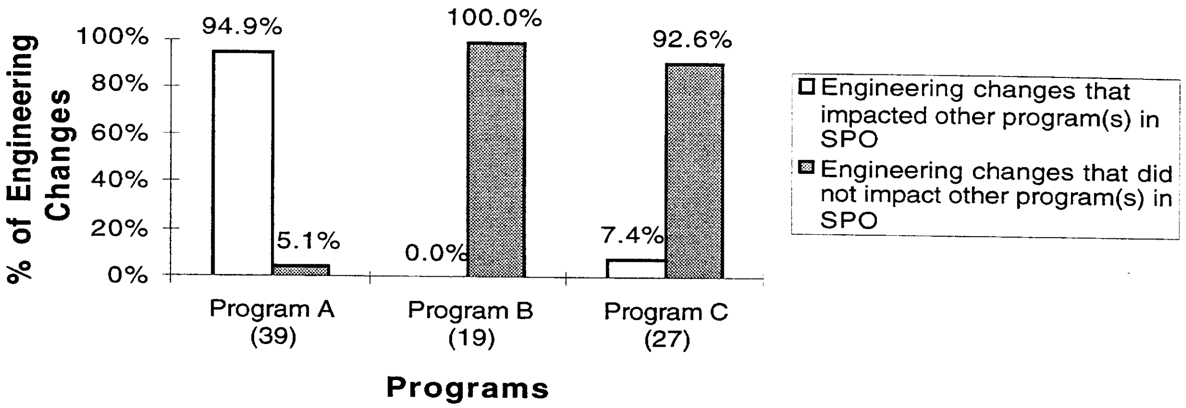
This section discusses the impact of engineering changes across programs managed by different program offices in the same SPO. Figure 5-14 shows the proportions of engineering changes in each of the three case-study programs that impacted and did not impact at least one other program in the same System Program Office.



Based on all 118 engineering changes in database.

Figure 5-14: Impacts of engineering changes on other program in the SPO

Within the confines of the three case-study programs, Program A was the predecessor to Program B. In other words, the progress of Program B depended somewhat on that of Program A. In fact, engineering change data and interviews with program office and contractor personnel indicated that it was necessary for Program B to incorporate applicable engineering changes from Program A into its own design baseline. In addition, interviews with contractor personnel suggested that two engineering changes that involved realigning flight tests for Program C enabled other programs to share data from the flight tests.



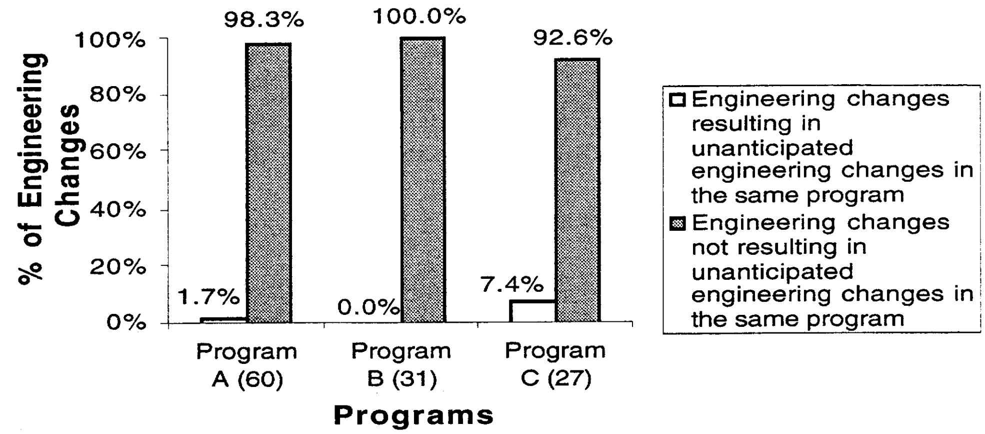
Based on 85 engineering changes affecting SS and/or MSS only.

Figure 5-15: Specification-normalized impacts of engineering changes on other programs in SPO

Figure 5-15 shows the specification-normalized results shown in Figure 5-14. While the patterns in the former approximated their counterparts in the latter, some differences in magnitudes of numbers require explanation. Many Program A engineering changes removed by the normalization were fixes to the already-built products that would not affect the design of the Subsystem B1 of Program B. Therefore, the percentage of Program A engineering changes that impacted Program B dropped from 12.1% to 5.1%. All Program B engineering changes that descriptive data indicated as having impacted other programs were eliminated through normalization, which would explain 0.0% for Program B in Figure 5-15.

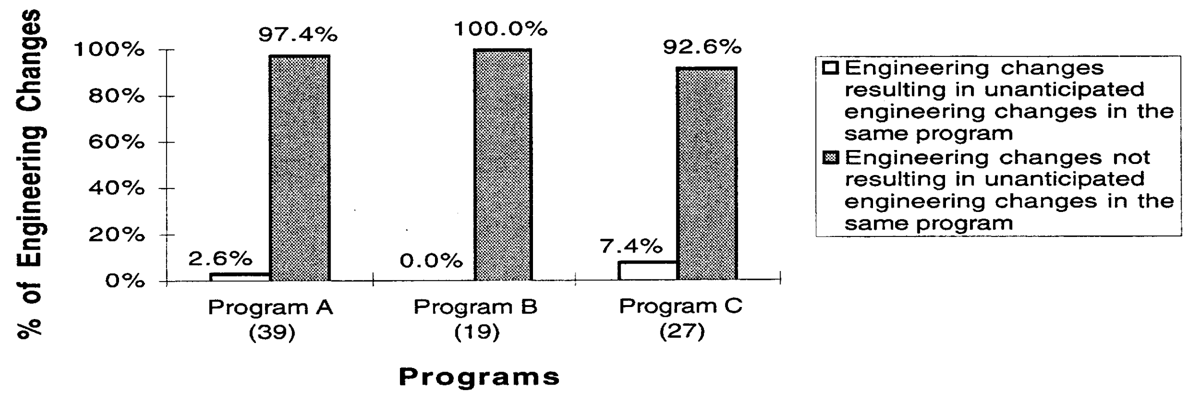
5.7 Engineering Changes Leading to Unanticipated Engineering Changes in the Same Program

Another question regarding impacts of engineering changes is whether an engineering change resulted in subsequent, unexpected engineering changes. This impact area should not be confused with planned engineering changes. Figure 5-16 shows the results, which indicate that engineering changes seldom lead to surprises in the same program that require additional engineering changes. The results imply that the configuration control process, with the primes and suppliers[106] preparing and submitting ECPs, and users and program offices reviewing ECPs, has been conducive to understanding the impacts of engineering changes on a change-by-change basis. The quantitative results are nearly identical when the data are normalized, as shown in Figure 5-17 below.



Based on all 118 engineering changes in database.

Figure 5-16: Engineering changes leading to unanticipated engineering changes over the same issue in the same program



Based on 85 engineering changes affecting SS and/or MSS only.

Figure 5-17: Specification-normalized engineering changes leading to unanticipated engineering changes over the same issue in the same program

---

[106] Suppliers may have a less apparent role than the other parties in the ECP preparation and evaluation process.

5.8 Summary of Findings about Impacts of Engineering Changes

This section reviews the key findings detailed earlier in this chapter and discusses the implications of these findings. Appropriate figure numbers are included to refer back to the detailed discussions.

The data presented earlier in this chapter indicated that every engineering change examined as part of this research had a near-term cost impact, and that the near-term cost would almost always be higher than would have been the case without the engineering change (Figure 5-1). Thus, it would be desirable, in general, if the engineering changes were made to be responsive (able to meet shifted expectations) to evolutions in user needs and technology. It would be less effective to have prime contractors and suppliers do rework (Figure 5-10 and Figure 5-12) in order to meet expectations that should have been met in the first place (Figure 5-8). In addition, it appeared that engineering changes in the three case study programs seldom resulted in exceeding product performance expectations (Figure 5-8). Similarly, earlier discussions also indicated that engineering changes infrequently led to less work for prime contractors and their suppliers. In other words, engineering changes rarely seem to relieve contractors from their contracted requirements (Figure 5-10 and Figure 5-12). Data and discussion in the chapter also showed that engineering changes, in general, enabled the contractors to meet customer expectations. The cost increases for the various communities in product development represented the "prices" paid for meeting these expectations.

The research also found that engineering changes seldom led to program schedule delays (Figure 5-6). This finding does not imply that every task on the programs was done at the expected time. However, the finding does seem to imply that the tasks were managed in such a way as to not adversely impact program schedule. Even in cases where some engineering changes led to program schedule delays, those changes were in the small minority, and the delays had to be accepted, or else capabilities could not be realized. Not allowing program schedule slips unless absolutely necessary implied great discipline in controlling engineering changes.

Program C was able to make many engineering changes in response to evolutions in user needs and technology without much rework for the prime contractor and suppliers (Figure 5-10 and Figure 5-12) and no program schedule slip. Several factors may have contributed to these results. First, Program C recognized schedule as a priority. Second, the program's ability to properly define requirements early provided opportunities to be responsive to evolutions in user needs and technology. Finally, the use of mature, as opposed to developmental, technologies helped in reducing schedule risk.

Finally, the discipline and capabilities of personnel involved on the programs were perhaps best demonstrated by the finding shown in Figure 5-16. If Goode and Machol were correct that complexity of the system is not well understood unless the nonlinear effects of changes are well elaborated[107], then the complexity of the systems on the three programs appear to have been well managed on a change-by-change basis because issues believed to be resolved by engineering changes rarely created surprises requiring subsequent engineering changes.

5.9 Chapter Summary

This chapter focused on the impacts of engineering changes. Findings and lessons learned in this regard were developed based on engineering changes collected as part of this research, and the characteristics of the three case-study programs.

In order to further study the causes and impacts of engineering changes in the three case-study programs, it would be useful to explore the pair-wise relationships between causes, impacts, and time. These relationships are the topics for Chapter 6.

---

[107] Goode, Harry H. and Robert E. Machol. *System Engineering: An Introduction to the Design of Large-Scale Systems*. New York, NY: McGraw-Hill Book Company, Inc. 1957, pp.5-6.

This page is intentionally left blank.

6. Relationships between Primary Causes, Impacts, and Time

This chapter provides a further discussion on the nature of engineering changes based on data from the three case-study programs. More specifically, this chapter examines three relationships involving engineering changes: impacts vs. primary causes, impacts vs. time, and primary causes vs. time. The discussion here seeks to identify broader trends and patterns than those explored in Chapters 4 and 5.

6.1 Impacts vs. Primary Causes

The analysis discussed in this section is based on the quantitative results presented in Chapters 4 and 5. Chapter 4 discussed the relative importance of causes of engineering changes in each of the three case-study programs, and identified the dominant causes across the three case-study programs. Chapter 5 presented a discussion of the impacts of engineering changes in terms of seven impact areas. In light of these findings, it would be desirable to examine whether some primary causes result in engineering changes of high impact. A high-impact engineering change is defined here as one that affects at least four out of the seven impact areas examined in Chapter 5. In this sense, "high impact" is a short-cut designation for "high scope of impact," which is different from "high magnitude of impact."

An example of the application of the definition and related considerations is shown in Table 6-1. Engineering changes included in Table 6-1 are those in all three programs that were due primarily to requirements definition issues. The engineering change identification numbers (Column 1 in Table 6-1) have been modified to disguise the identity of the three case-study programs.

1	2	3	4	5	6	7	8	9	10	11
Engineering Change Number Designation	Primary cause (with causal sub-categories from Table 4-1 also noted)	Impact on near-term cost; 1=yes, 2=no.	Impact on program schedule; 1=yes, 2=no.	Impact on product performance with respect to expectations; 1=yes, 2=no.	Impact on prime contractors' work; 1=yes, 2=no.	Impact on supplier(s)' work; 1=yes, 2=no.	Impact on other SPO programs; 1=yes, 2=no.	Engineering changes leading to unexpected, subsequent engineering changes in the same program; 1=yes, 2=no.	Number of "yes" impacts	Simple Statistics
1	1B	1	2	1	1	2	1	2	4	Average number of areas impacted 4.4
2	1A	1	2	1	1	1	1	2	5	
3	1B	1	2	1	1	1	2	2	4	
4	1A	1	2	1	1	1	1	2	5	
5	1A	1	1	1	1	1	1	2	6	
6	1A	1	1	1	1	1	1	2	6	
7	1A	1	2	1	1	1	1	2	5	
8	1A	1	2	1	1	1	1	2	5	
9	1A	1	2	1	1	1	1	2	5	
10	1A	1	2	1	1	1	2	2	4	
11	1A	1	2	2	1	1	1	2	4	
12	1A	1	2	2	1	1	1	2	4	
13	1A	1	1	1	1	1	1	2	6	
14	1A	1	1	1	1	1	1	2	6	
15	1A	1	2	1	1	1	1	2	5	
16	1A	1	1	1	1	1	2	2	5	
17	1A	1	2	1	1	1	2	2	4	
18	1B	1	2	1	1	2	2	2	3	
19	1A	1	2	1	1	2	2	2	3	
20	1A	1	2	2	1	2	2	2	2	
21	1A	1	2	1	1	2	2	2	3	
22	1B	1	2	1	1	2	2	2	3	
23	1A	1	2	1	1	1	2	2	4	

Number of engineering changes in all three programs due to the primary cause = **23**

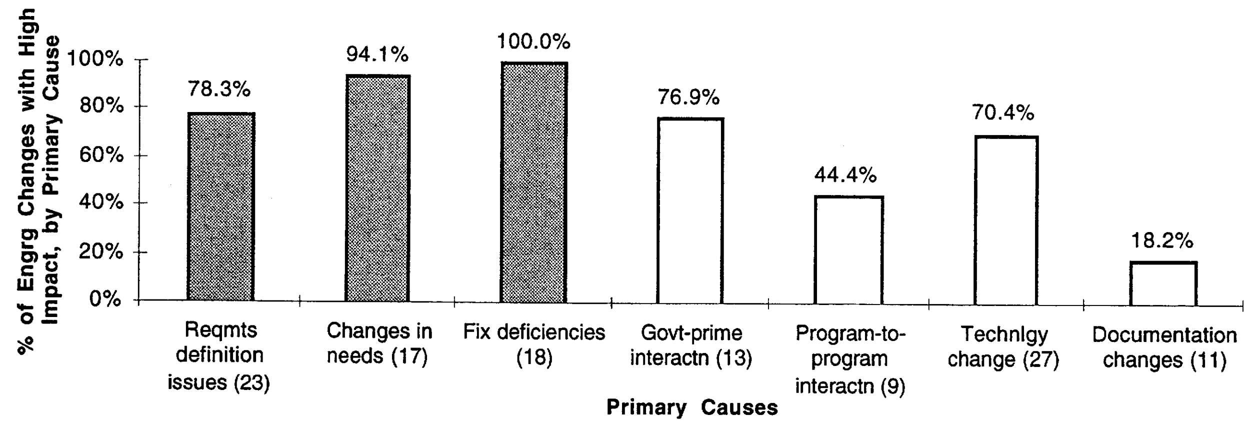
Table 6-1: Example data for impacts vs. primary causes study

Each row in Table 6-1 contains data indicating whether an impact area is affected by each engineering change. For example, Chapter 5 presented four ways in which product performance with respect to expectations may be impacted by an engineering change. If an engineering change affects product performance in any of the four ways, it is assigned the numerical designation “1” in Column 5 of Table 6-1; otherwise, it is assigned a numerical designation “2”, which indicates that the impact area is not affected by the engineering change. Summing the number of “1” entries across each row yields the number of areas impacted by the engineering change in that row. This sum is then given in the "Number of 'yes' impacts" column (Column 10) in Table 6-1. A sum of four or more "yes" designations means the engineering change is considered to have had "high impact".

Using the complete table for all primary causes has resulted in two classes of results. The first quantifies the percentage of high-impact engineering changes due to each primary cause, while the second quantifies the mean (average) number of areas impacted by the engineering changes due to each primary cause.

6.1.1 Percentage of High-Impact Engineering Changes due to each Primary Cause

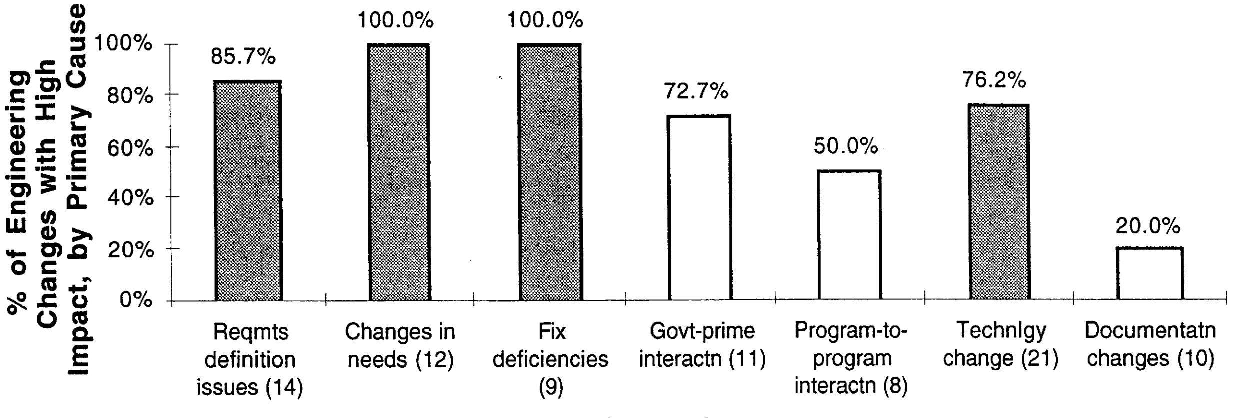
Figure 6-1 shows the percentage of high-impact engineering changes due to each primary cause. The figure is based on the comprehensive set of engineering change data, and the number of engineering changes from all three programs due to each primary cause is indicated in the labels on the horizontal axis. The first bar in Figure 6-1 is a result of summing the number of engineering changes in Table 6-1 that impacted four or more areas out of seven, and dividing the sum by 23, which represents the total number of engineering changes due mainly to requirements definition issues in all three case-study programs. Other bars were obtained in similar fashion.



Based on comprehensive set of engineering changes (118) across the three programs.

Figure 6-1: Percentage of engineering changes with high impact due to each primary cause

Figure 6-1 shows that three out of the four dominant causes of engineering changes identified at the end of Chapter 4 (i.e., requirements definition issues, changes in needs, and fixing deficiencies) appeared to be the top three causes most likely to lead to high-impact engineering changes. Also according to Figure 6-1, government-prime interactions was another primary cause mostly likely to result in high-impact engineering changes. This means that if the causes of engineering changes were weighted by scope of impacts, government-prime interactions would qualify as another dominant cause of engineering changes.



Based on total of 85 engineering changes affecting SS and/or MSS only.

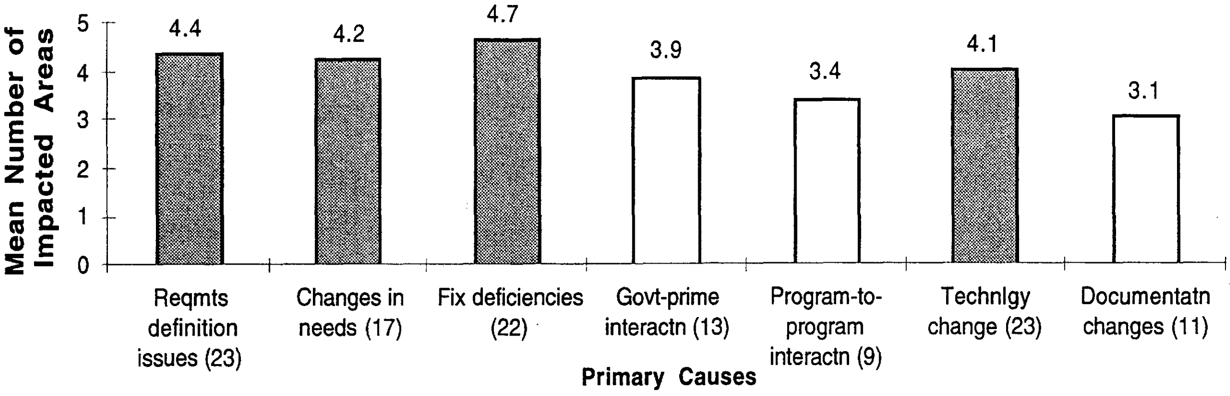
Figure 6-2: Specification-normalized percentage of high-impact engineering changes vs. causes

The specification-normalized version of Figure 6-1, shown in Figure 6-2, shows that the four dominant causes identified in Chapter 4 (i.e., requirements definition issues, changes in user needs, the need to fix deficiencies, and changes in technology) were the major sources of high-impact engineering changes. It should also be noted that the government-prime interactions is not far behind in terms of the percentage of engineering changes that could be construed as having high impact.

6.1.2 Mean Number of Areas Impacted vs. Primary Causes

An alternative method for analyzing the relationship between impacts of engineering changes and primary causes is to examine the mean number of areas impacted by engineering changes due to each primary cause. The mean number of areas impacted by engineering changes due to requirements definition issues was the result of summing the magnitudes of the numbers in the "Number of 'yes' impacts" column in Table 6-1, and dividing the sum by 23, which represents the total number of engineering changes in the three programs that were due primarily to requirements definition issues. The resulting mean (average), 4.4, is displayed on top of the first bar in Figure 6-3. The same procedure was used in computing the other mean values presented in Figure 6-3.

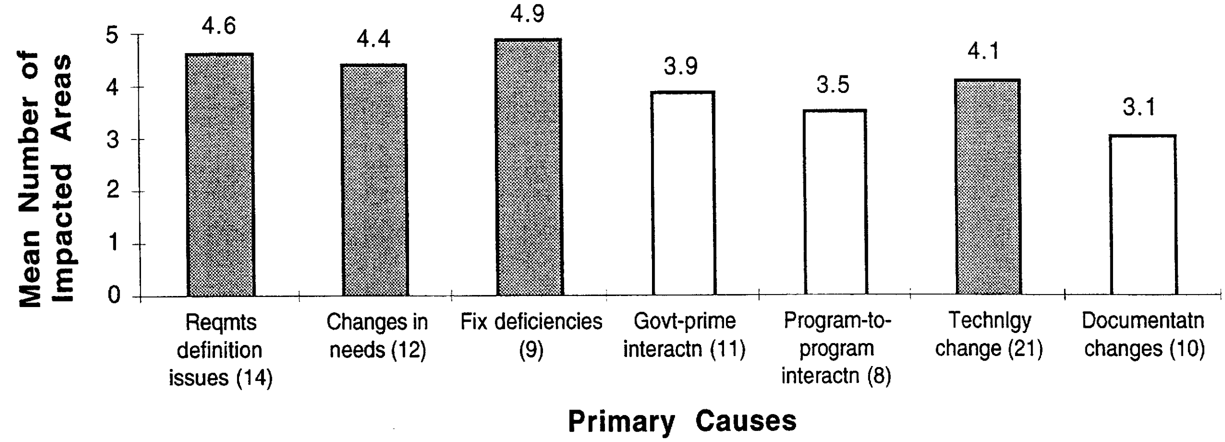
Using this measure, and basing the analysis on the comprehensive set of engineering change data collected for this research, Figure 6-3 indicates that engineering changes due primarily to the four dominant causes identified in Section 4.5.2 were, on the average, of high impact. In a statistical sense, each measure of mean displayed in Figure 6-3 can be interpreted as the expected value of the number of areas that would be impacted by an engineering change due to each primary cause.



Based on all 118 engineering changes in the three case-study programs.

Figure 6-3: Mean number of areas impacted by engineering changes due to each primary cause

The result is also robust when only the engineering changes affecting high-level specifications were considered, as shown in Figure 6-4. In the results with and without specification-based normalization, an engineering change due primarily to government-prime interactions could be expected to impact almost four out of the seven areas, thereby elevating this cause to another major source of high-impact engineering changes.



Based on total of 85 engineering changes affecting SS and/or MSS only.

Figure 6-4: Specification-normalized mean number of areas impacted by engineering changes due to each primary cause

6.2 Variation of the Scope of Impact Over Time

The analysis of the impact vs. time relationship, using the engineering change data from the three case-study programs, was motivated by the often-heard observation that the cost of making an engineering change increases with time[108]. The question applicable to this research is: Does the number of areas (out of the seven discussed in Chapter 5) impacted by engineering changes increase with time? In other words: Does the scope of the impact of engineering changes become broader over time?

The analysis was conducted by first considering when the first ECP on each program was received by the program office. Between that date and the date of receipt of the last available ECP from that program (as of 17 November 1997) was the time interval that was further divided into five smaller, equal intervals, or "time phases".

---

[108] The implication of this observation is that in developing a complex product, engineering changes introduced in later stages of the design process have a higher probability of creating a greater chain reaction of impacts involving many other components and hence result in considerably higher costs, compared with engineering changes made in earlier stages of the design process. An example of such observation was discussed in Boppe, Charles W. "Complex Product Design Process: Elements, Relationships, Process Flow." MIT 16.870 Aerospace Product Design lecture notes. Fall 1996, focusing on data shown for a major electronic component.

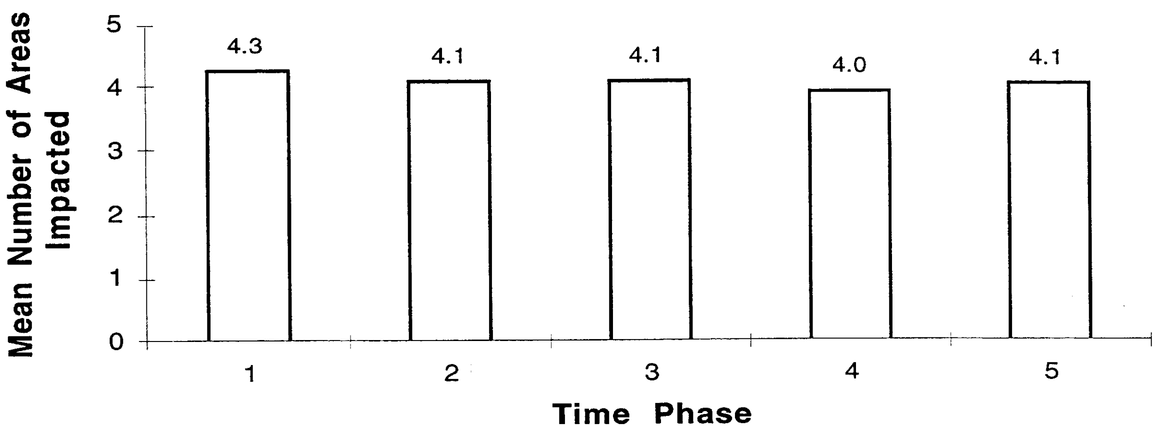
The example data shown in Table 6-2 represents the "Time phase 1" portion of the data used for this analysis. The engineering changes in this interval ("time phase") are those received during the first of the five intervals of each program as defined above. Their identification numbers in Column 1 of Table 6-2 have been modified to disguise the identity of the three case-study programs. It is useful to understand that these engineering changes are not necessarily the same ones as those shown in Table 6-1 because the data are now sorted in terms of time, not in terms of primary causes, as was the case before. Furthermore, the number of impact areas affected by each engineering change in the three case-study programs was already known, as described in Section 6-1.

1	2	3	4
Engineering Change Number Designation	"Time phase" (1, 2, 3, 4, or 5) in which the ECP was received	Number of areas impacted ("Number of 'yes' impacts" from Table 6-1)	Simple statistics
1	1	3	Average number of
2	1	3	areas impacted
3	1	6	4.3
4	1	6	
5	1	3	
6	1	6	
7	1	5	
8	1	3	
9	1	6	
10	1	5	
11	1	4	
12	1	5	
13	1	5	
14	1	3	
15	1	3	
16	1	3	
17	1	4	
18	1	4	

Number of engineering changes in "time phase 1" = **18**

Table 6-2: Example data for impacts vs. time analysis

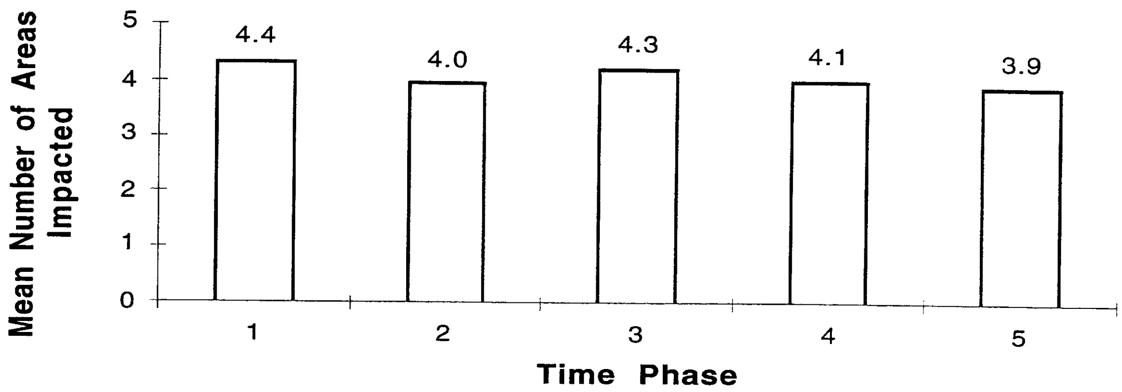
The mean (average) number of impact areas affected by engineering changes in this time interval is obtained by dividing the sum of the numbers in Column 3 of Table 6-2 by 18, which represents the total number of engineering changes received during the first of five time intervals of each of the three case-study programs. The result, 4.3, is shown in Column 4 of Table 6-2, as well as above the first bar in Figure 6-5. The mean number of areas impacted by engineering changes in other time intervals were obtained in the same fashion.



Based on all 118 engineering changes in database.

Figure 6-5: Scope of impact of engineering changes vs. time

The results in Figure 6-5 indicate that the mean number of impact areas affected by engineering changes in the three case-study programs remains relatively constant over time. Why the seeming discrepancy between the often-heard increase-of-cost of making engineering changes over time and the essentially constant scope (or breadth) of impact over time? The former approximates the magnitude of average cost of making engineering change at different product life cycle phases, without addressing impacts other than the cost of making such engineering changes. The latter shows the time dependence of the number of areas impacted without addressing the magnitude of the impact in each area. In short, the two observations pertain to different aspects of the impacts of engineering changes. Specification-normalized results shown in Figure 6-6 also demonstrate the nearly time-independent scope (or breadth) of impact of engineering changes.



Based on 85 engineering changes affecting SS and/or MSS only.

Figure 6-6: Specification-normalized scope of impact of engineering changes vs. time

6.3 Primary Causes Over Time

Finally, the third relationship addresses the question: Do engineering changes, due to certain primary causes, tend to occur more frequently at certain times during the product development process? This question is somewhat more difficult to address than the previous two, since within each time interval, potentially seven[109] primary causes could be present in each of the three programs.

Two steps have been taken in response to this difficulty. First, each primary cause was examined one at a time, program by program, in order to verify whether the engineering changes due to that primary cause were concentrated in certain time intervals in the course of all three programs. Second, high-level causes of engineering changes were used in this analysis to ensure that results are based on sufficient numbers of engineering changes. These high-level causal categories, repeated here from Section 3.3, are (1) requirements-related issues; (2) the need to fix deficiencies; (3) program interaction; (4) technological changes; and (5) documentation changes.

The results, shown in Appendix E, are quickly summarized here. Namely, no discernible patterns emerge from this analysis. The patterns appear to be random across the three programs.

---

[109] Eight in total if all causes of engineering changes included in the framework in Section 3.3.1 were used. Recall from Chapter 4 that no engineering changes in the three case-study programs were found to be due primarily to "funding reduction after program start".

Aggregating the primary causes, as just noted, did not bring any greater clarity to the results Consequently, no meaningful conclusion can be drawn based on this analysis.

6.4 Summary of Findings

This section summarizes the findings discussed earlier in the chapter. This chapter has presented a discussion of three relationships among primary causes of engineering changes, impacts of engineering changes, and time in order to explore further the nature and implications of engineering changes in the three case-study programs.

The analysis of the relationship between primary causes and impacts showed that engineering changes due mainly to the four dominant causes across the three case-study programs tended to be of high-impact. An engineering change was defined to have had high impact if it affected at least four of the seven areas identified. In this sense, "high impact" is a short-cut designation for "high scope (or breadth) of impact," which is different from "high magnitude of impact." This result was supported by data on the percentage of engineering changes with high impact due to each primary cause. This result was further verified by examining the mean number of areas impacted by engineering changes due to each primary cause.

The distribution of impacts over time showed that the mean number of areas impacted by engineering changes (i.e., the scope of impact) remained relatively constant over time. However, the finding did not address the degree of severity, or the magnitude, of each impact. For example, it could not shed light on the order of magnitude of the near-term cost impact, or the labor-hours required to implement engineering changes made at different times. Therefore, the finding only addressed the scope (or breadth) of impact of engineering changes over time.

Finally, the primary causes vs. time analysis tentatively revealed no particular pattern of causes of engineering changes over time. In other words, engineering changes occurred as they did, and their causes did not reveal any particular pattern in terms of their frequency distribution at certain times in the course of the product development process in the three case-study programs.

7. Conclusions

This chapter reviews the research documented in this thesis. It first provides a brief discussion of the research objectives, key questions, and research method. It then highlights the key findings. Finally, it addresses the limitations of the research and the findings, and suggests directions for future research on engineering changes.

7.1 Review of Research Objectives, Key Questions, and Research Design

This research was conducted with two objectives in mind. One objective, in light of the gaps of knowledge identified in existing engineering change-related literature, was to contribute new knowledge in the area of engineering changes by concentrating on the fundamental nature, the causes and impacts, of Class I engineering changes in the context of US defense aerospace product development. The second objective was to develop guidelines for reducing defense aerospace product development cycle time and cost.

Achieving these objectives required an understanding of Class I engineering changes (heretofore referred to as engineering changes). These are engineering changes that fundamentally modify the form, fit, and/or function of a defense product in such a way that the functionalities or physical configuration of the product are different before and after the change. Specifically, three key questions central to this research were posed about engineering changes:

- What are the causes and impacts of engineering changes?
- What are specific product development practices that would help reduce the number of undesirable engineering changes?
- What can the acquisition customer organizations do to reduce the number of undesirable engineering changes?

In order to gain sufficient insight into these key questions, the research was structured to be case study-based. The case-studies focused on three major United States Air Force (USAF) aircraft acquisition programs in the electronics sector. All three programs (Programs A, B, and C) are the responsibility of a single System Program Office (SPO). Data on 118 engineering changes were collected from contractor-submitted Class I Engineering Change Proposals (ECPs) archived at the SPO. In addition, supporting documents pertaining to the three programs, as well as to the specific systems and subsystems within each of the three programs, were collected in order to assist in developing a comprehensive understanding of these engineering changes. Furthermore, engineers and managers from three prime contractors (X, Y, and Z) and the program offices were interviewed to obtain their perspectives on the programs and the engineering changes. Finally, frameworks for categorizing causes and impacts of engineering changes were proposed and utilized to enable the analysis of the data collected. The analysis led to the findings highlighted below.

7.2 Summary of Major Findings

7.2.1 Causes of Engineering Changes

Two key findings pertaining to the causes of engineering changes in the three case-study programs should be highlighted. First, the four dominant causes of engineering changes *across the three programs* were found to be the design assumptions made in the initial phases of the programs, evolution of user needs as programs progressed over time, the need to correct design/product deficiencies, and changes in technology. Second, however, the combinations of dominant causes were different *from program to program*, and were strongly dependent on the characteristics of the individual programs.

7.2.2 Impacts of Engineering Changes

The findings pertaining to the impacts of engineering changes in the three case-study programs encompassed seven areas, or ways, in which the program and communities involved in defense aerospace product development could be affected by engineering changes. For example, it was found that most of the engineering changes tended to increase the near-term cost of the programs. On the other hand, only a small share of the total number of engineering changes in the three programs impacted program schedule. In addition, all engineering changes that impacted schedule always delayed the program. In terms of product performance, the majority of engineering changes in the three programs appeared to have been implemented to meet product performance expectations, either by meeting shifted expectations or by meeting original expectations. Furthermore, it was found that engineering changes rarely relieved prime contractors and suppliers from their contracted requirements. In addition, whether engineering changes on one program impacted other programs within the same SPO depended significantly on the relationship between the programs. Finally, engineering changes in each of the three case-study programs rarely resulted in subsequent, unanticipated engineering changes in the same program.

7.2.3 Relationships between Causes, Impacts, and Time

The pair-wise relationships between causes and impacts of engineering changes and time were also explored. It was found that the engineering changes due to the four dominant causes identified in Section 7.2.1 were most likely to be of high impact - at least four out of seven areas (discussed in Section 7.2.2) were affected by an engineering change. Furthermore, the average number of areas impacted by engineering changes in the three case-study programs remained relatively constant over time. Finally, no particular relationship between the causes of engineering changes and time was found.

7.2.4 Defense Aerospace Product Development Issues

The three case-study programs provided some lessons learned about defense aerospace product development. The lessons learned pertain to the use off-the-shelf subsystems, the use of the associate contractor arrangement in development programs, the use of IPTs and early supplier integration into product development, and the use of mature technologies.

The Program A case study provided an important lesson about the use of off-the-shelf subsystems. Subsystem A1 was an advanced subsystem developed and produced for another branch of the armed services. In this case, the initial assumption that it could be easily adopted, with little modification, for operations in a significantly different environment led to substantial redesigns on an off-the-shelf item. The implication is that the use of an off-the-shelf subsystem, without a firm understanding of the operational environment within which the subsystem must function, may lead to substantial redesigns, thereby eroding the possible benefits of using the off-the-shelf subsystem in the first place.

The Program B case study provided some insight into the use of the associate contractor arrangement (i.e., having two prime contractors) on development programs. The use of the associate contractor arrangement during full-scale development necessitated two engineering changes to address one change issue if it affected both associate contractors. Government and contractor personnel also pointed out that in the development of a complex product, such as Subsystem B1, the use of the associate contractor arrangement increased the possibility of specifications managed by the two separate contractors becoming inconsistent. The observations, however, should not be taken as a commentary on the merits of developmental programs in which multiple prime contractors develop equivalent but competing products with the understanding that there will be an eventual downselect to one prime contractor.

Findings related to the use of integrated product teams (IPTs) and early supplier integration into product development were also derived from the case-study programs. First, it was found that the prime contractor's use of IPTs, for development-related activities, helped reduce the proportion of engineering changes that were due primarily to requirements definition. Second, despite the early involvement of key suppliers in Programs A and B, some requirements definition issues were found to remain, necessitating redesigns later in the programs. The case studies provided indications that, had IPTs been used during the development phases of these programs, the prime contractors may have been able to have a better understanding of the capabilities of their key suppliers and hence be better equipped to clarify some of the key requirements early in the programs, thereby avoiding some undesirable engineering changes and significant redesigns.

Finally, the experience of Program C may illustrate some benefits associated with using mature technologies. The use of mature, as opposed to developmental, technologies when feasible enabled Program C to make numerous engineering changes to quickly achieve incremental product improvements. In addition, the use of mature technologies helped Program C make these engineering changes without program schedule delay.

7.3 Limitations of the Research and the Findings

There are at least three limitations of the research and the resulting findings that should be mentioned. The limitations pertain to the case study approach, the scope of the research, and the lack of direct inputs from the user community and subcontractors.

One major limitation of the research is that it was based on case studies focusing on three aircraft programs in the electronics sector under the same SPO. While focusing on these case-study programs within the same SPO helped control variability that may exist across different SPOs, it may be worth noting that the lessons learned about defense aerospace product development on the basis of these three case studies may not be directly applicable to other sectors of the defense aerospace industry.

The broad scope of the research can be considered as another limitation. The research studied seven possible impacts of engineering changes without addressing any of the them in detail. For example, no useful data were available to quantify the cost of making Class I engineering changes across the user community, the acquisition community, and/or the contractors.

Finally, direct inputs from the user community and subcontractors (suppliers) may have provided additional insights into the three case study programs. However, this would have required permission from both the SPO and prime contractors to obtain access to these sources, and the time required to obtain such permission would have been prohibitively long for this research.

7.4 Suggestions for Future Research

In light of the limitations of this research identified above, several directions of future research can be suggested:

- The research might be repeated using other case-study programs in the electronics sector, perhaps by focusing on programs in the same SPO that managed the three programs studied in this research. The goal would be to understand whether the findings and lessons learned here apply to other programs.

- A related suggestion would be to study programs under a single SPO that started at different times. The goal would be to evaluate the possible effects of various acquisition reform initiatives on engineering changes.
- The research reported here may also be repeated using case studies in other sectors of the defense aerospace industry. One goal of doing so would be to determine the applicability of the findings and lessons learned in other sectors.
- It may be useful to study the cost of making Class I engineering changes borne by different communities involved with these engineering changes. Engineering change descriptive data indicated that while some engineering changes made to correct deficiencies may be considered as being "no cost" to the government, their implementation required additional work by the user community. Can such work be systematically studied and understood in terms of monetary expenditures? However, the experience of the research effort reported here was that gathering credible cost data is problematic, so it may be very difficult to explore this area.
- Finally, instead of simply expanding the data collection effort to include the user community and the suppliers, it may be possible to focus on the engineering changes that may highlight issues at the prime contractor-supplier interface. This interface was one that this research may not have adequately addressed due to lack of direct data from the suppliers.

Appendix A. Details of Engineering Change-Related Literature Review

This appendix presents eight engineering change-related publications that were reviewed in detail in support of this research. A summary of these publications are first presented in a table format, then the details of each review are included.

	Research method & setting	**Type of data collected**	**Interface(s) studied**	**Type(s) of changes studied**	**Nature of changes studied**	**Findings**
Barkan	Summarizing findings by other researchers.	Research results of others.	Focused on both design and production.	Engineering changes in general; no explicit differentiation.	Causes and impacts of engineering changes alluded to, but in the context of why US engineering efforts take twice as long as those for similar products in Japan do.	Factors explaining the differences between US & Japanese engineering productivity were offered.
Hegde et al.	Case study of one division within a large company.	Engineering change order (ECO) data; part flow times in mfg.; descriptive data on managerial behavior.	Design-manufacturing interface within one business unit of large company.	Number of design changes in specifications after traveler release[110].	Focused on the impact of ECOs on the time necessary to complete the mfg. of parts.	ECOs were detrimental to mfg. completion time.
Coughlan	Case study based on 12 products from 4 divisions in the same company.	Survey data on products and mfg. engineering staff experience; engineering change data from company file.	Design-manufacturing interface to study contribution of mfg. engineering to product development.	Focused on what are called Class II (in MIL-STD terms) engineering changes.	Focused on aspects of mfg. engineering involvement in product development that influence manufacturability-related changes.	Experienced mfg. engineering staff on product development reduces changes; earlier involvement is not necessarily better in reducing changes.

---

[110] Traveller is a card on which job history is recorded, and moves with the job as it proceeds from one operation to the next. See Hegde et al.: 1992, p.345.

	Research method & setting	Type of data collected	Interface(s) studied	Type(s) of changes studied	Nature of changes studied	Findings
Ettlie	Survey study across many industries to study early mfg. involvement (EMI) in conceptual stage of product development (PD).	Return on investment, training for product development team members; engineering changes; role of mfg. staff on product development.	Design-manufacturing interface.	Engineering changes prior to start of volume production.	Reduction of engineering changes via EMI.	Fewer the changes before production start, more ROI; more EMI, fewer changes; more training, more EMI.
Fricke et al.	About 20 interview-based case studies	Interview results. Very little numerical data.	Product life cycle.	Changes of various scopes and seriousness.	Cause and impacts of engineering changes; strategies to manage engineering changes.	High-level categorization of causes & impacts of engineering changes; strategies for engineering change management.
Kick	Case study of a new product development program at one company.	Descriptive data about existing processes.	Product life cycle.	None.	Engineering change management process.	Linked changes to system integration; identified barriers to proper system integration.
Hooper	Case study of a corrective action process in the Boeing 777 program.	Descriptive data about process; numerical data about errors (changes).	Design-manufacturing interface.	Errors in the 777 electrical wiring system.	Focused on change implementation; causes and impacts discussed, but in context of interface studied.	Improved the 777 Electrical Corrective Action Process.
Wright	Literature review.	Papers and research projects related to engineering changes from 1980 to 1995.	Predominantly design-manufacturing interface.	Engineering changes after production start.	Tools for change implementation and methods to improve change management process.	Existing work done from mfg. perspective, not product development/business perspective; suggestions for future research directions.

Table A-1: Summary of literature review

Barkan[111]

Background

Barkan's publication was a chapter *in Integrating Design and Manufacturing for Competitive Advantage.* The chapter was largely based on research carried out by others. It studied possible reasons why US industries lagged behind their Japanese counterparts "...in terms of engineering productivity as measured by total elapsed time required to develop new products, by the total engineering man-hours required to develop new products, and by the quality of the initial product design as measured by design changes late in the cycle, field defects, and recalls."[112] Although the role of engineering changes was not the focus of study, it was one of the major areas addressed.

Hypotheses Tested or Questions Asked

The main question Barkan sought to answer was: "Why should U.S. engineers require up to twice the engineering manpower for twice the time in order to design comparable products [as compared to their Japanese counterparts]?"[113]

Research Method

The research was conducted by consolidating results found by other researchers.

Findings

Barkan contended that the discrepancy in engineering productivity between American and Japanese industries had to do with use of outside suppliers, working hours, overlapping design activities, engineering procedures, and the control of engineering design changes[114]. His discussions on each of the reasons, while all important, only those on design changes are highlighted here.

---

[111] Barkan, Philip. "Productivity in the Process of Product Development - An Engineering Perspective". *Integrating Design and Manufacturing for Competitive Advantage*, Gerald Susman, Ed. New York, NY: Oxford University Press, 1992, pp.56-68.

[112] Barkan: 1992, p.56.

[113] Barkan: 1992, p.56.

[114] Barkan: 1992, pp.56-59.

Sullivan[115], cited by Barkan, showed that the number of engineering changes per week made by US auto makers peaked near production start, while the same made by Japanese auto makers peaked not too long after project start. Barkan proposed to attribute the difference, and the differences in scope of the engineering changes made at different times to eight factors[116]:

1. Completeness of product definition,
2. Restriction of design innovations to proven technology,
3. Integration of experience,
4. Role of prototypes in enhancing design productivity,
5. Interdisciplinary experience and simultaneous engineering,
6. Structured methodologies and disciplined procedures,
7. Superior support infrastructure, and
8. Reduction in dimensional errors.

Two observations are noted here about these 8 factors in Barkan's work. First, they were identified by Barkan as being able to explain how the US industries (automotive, photocopier) he examined via the works of others might be able to make their engineering changes earlier, when impacts are localized. Second, they can be applied to different levels of a system when the system is decomposed into a hierarchy. For example, "complete product definition" implied having a good understanding of system-level requirements, while "reduction in dimensional errors" can be applied to the detail part-level of the system, and "integration of experience" can be applied to individuals who build the parts, or individuals writing the requirements. The second observation in turn implied that the engineering changes that these factors have an impact on also apply to different levels of the system. This implication may become important when deciding which types of engineering changes to focus the research on.

---

[115] Sullivan, L. P. "QFD: The Beginning, The End, and the Problem In-Between." Quality Function Deployment, A Collection of Presentations and Case Studies. Dearborn, MI: American Suppliers Institute, 1987. As quoted in Barkan: 1992, p.58.

[116] Barkan: 1992, pp.59-65.

Hegde, Kekre, and Kekre[117]

Background

The empirical study documented in the paper by Hegde et al. attempted to identify factors at the design-manufacturing interface that were responsible for manufacturing delays. The paper itself focused on empirically attributing manufacturing delays to engineering change orders (ECOs). For the ECOs, only their quantity was available to Hegde et al. since the company at which the study was conducted kept no record on the nature of its ECOs[118].

Hypotheses Tested or Questions Asked

There were no explicit statements of hypotheses in the exploratory study as documented in the paper by Hegde et al. Inferring from the contents of the paper, a plausible hypothesis could have been: Engineering change orders are major factors causing time delays in the manufacture of parts[119].

The authors of the paper wanted to relate high-level management issues to engineering change orders (ECOs). More specifically, they wanted to understand from the interactions between manufacturing and design engineering, purchasing, and quality assurance how engineering change orders lead to time delays in manufacturing[120].

Research Method

The research setting was a business unit (ABC) of a Fortune 500 company with each product line manager in charge of purchasing, marketing, engineering, and manufacturing[121]. From this business unit, Hegde et al. collected data, recorded by the company on "travellers"[122], from parts manufactured within the years 1988 and 1989. The researchers used the data to support the derivation of empirical relationships showing impacts of ECOs on manufacturing time.

Findings

---

[117] Hegde, G.G., Sham Kekre, and Sunder Kekre. "Engineering changes and time delays: A field Investigation." *International Journal of Production Economics*, Vol. 28. 1992. Elsevier Science Publishers B.V., pp.341-352.

[118] Hegde et al.: 1992, p.345.

[119] Hegde et al.: 1992, pp.341-342.

[120] Based on the discussion in Hegde et al.: 1992, p.342.

[121] Hegde et al.: 1992, p.344.

[122] According to the business unit at which the research was conducted, a "traveller" is a card that accompanies a part, and records its manufacturing history. Hegde, et al.: 1992, p.345.

Based on single- and multi-variable regression analysis on the data, the authors showed that each ECO increased the time each part spent in the manufacturing process by at least 11 days[123]. Finally, Hegde et al. indicated the necessity of conducting similar studies at different types of organizations[124].

Coughlan[125]

Background

The paper is yet another chapter in *Integrating Design and Manufacturing for Competitive Advantage*. It reports on an empirical study of engineering changes in newly developed products[126]. This detailed study that was able to derive from data lessons-learned about the design-manufacturing interface for product development in general[127].

Hypothesis Tested or Questions Asked

The empirical study presented in this paper sought to answer two questions[128]:

1. Is the avoidance of engineering change in newly developed products associated with the way manufacturing engineering staff are deployed during the product development process?

   There factors involved with the deployment of manufacturing engineers in product development were investigated[129]: manufacturing engineers' experiences, their emphasis on manufacturability of designs, and the phasing of the manufacturing engineers' deployment into product development. The impact of each factor on manufacturability-related engineering changes was investigated.
2. Is an association between the avoidance of engineering change and the way these engineering resources are deployed contingent on the development context?

---

[123] Hegde et al.: 1992, p.347-349.

[124] Hegde et al.: 1992, p.350.

[125] Coughlan, Paul D. "Engineering Change and Manufacturing Engineering Deployment in New Product Development." *Integrating Design and Manufacturing for Competitive Advantage*, Gerald Susman, Ed. New York, NY: Oxford University Press, 1992, pp.157-177.

[126] Coughlan: 1992, p.157.

[127] Coughlan: 1992, p.171-176.

[128] The questions taken as they are from Coughlan: 1992, p.158.

[129] Coughlan: 1992, pp.167-171.

With this question, Coughlan sought to know how relationships found in the previous question might be different depending on the newness of the product.

The term "development context" in the second question was used by Coughlan to address the degrees of product and process newness[130]. Newness[131], in turn, meant "...the degree of similarity of a product to other members of its family." In order to operationalize the concept of newness, its measurement "...included the degree to which preexisting product parts, process equipment, tooling and manufacturing methods were altered or redesigned to suit the requirements of the product under development.'[132]

Research Method

In order to seek the data that would help him answer the two basic research questions, Coughlan based his study on 12 electronic equipment products developed between 1983 and 1989 by four divisions of a major firm[133]. In other words, this is a case study-based research based on numerous, although somewhat similar, products.

The author of the paper collected data about engineering changes[134] and the hours[135] manufacturing engineers spent on product development from the company's internal files, while data regarding manufacturing engineers' experience with prior products were derived from responses from managers to survey questions[136]. From what one can see from the data presented in the paper, statistical analyses were done on the raw data to draw correlations when appropriate.

Findings

Coughlan found that engineering changes apparent to the customer[137] (akin to Class I engineering changes in MIL-STD terms) were avoidable prior to production start. On the other hand, manufacturability-related engineering changes were apparent to manufacturing but not the

---

[130] Coughlan: 1992, pp.161-162.
[131] Definition provided on p.162 of the paper.
[132] Coughlan: 1992, p.162.
[133] Coughlan: 1992, p.158.
[134] Coughlan: 1992, pp.164-165.
[135] Coughlan: 1992, p.160.
[136] Coughlan: 1992, p.161.
[137] Coughlan: 1992, p.158.

customer[138] (akin to Class II engineering changes in MIL-STD terms), were most detrimental to company. Therefore, a lot of effort was devoted in his study to the manufacturability-related engineering changes, and Table A-2 shows a summary of findings in this regard.

The most valuable lesson from Coughlan's study is that one should never ignore the importance of the experience carried over by ME staff from one product development project to another. Their experience reduced the number of manufacturability-related engineering changes after start of volume production in both newer and derived products at the firm where the research was conducted. A more subtle result from this study is that early (concept definition stage) involvement of ME staff on product development teams increased the incidences of manufacturability-related engineering changes for less-new products. Is there similar concern with the early involvement of customer and key suppliers on the prime contractor's defense aircraft product development efforts?

---

[138] Coughlan: 1992, p.158. Class I and Class II ECPs are discussed in more detail in the next chapter.

	ME staff experience & manufacturability-related engineering changes	**Emphasis on manufacturability and manufacturability-related engineering changes**	**Phasing of ME deployment & manufacturability-related engineering changes**
Newer products	The higher the experience of ME staff in product development team, the fewer the incidents of manufacturing related engineering changes[139].	Data available for statistical analysis showed that emphasis on manufacturability led to fewer incidents of manufacturability-related engineering changes, despite the incompleteness of information due to the relatively unprecedented nature of these newer products[140].	• Data showed no association between ME time expenditure during definition stage of product development and incidences of manufacturability-related engineering changes[141]. • During verification stage of product development, the incidences of manufacturability-related engineering changes were fewer as ME spend more time in this stage[142].
Less-new products	Same as above[143].	Data did not show association between ME's emphasis on manufacturability and manufacturability-related engineering changes[144].	• Incidences of manufacturability-related engineering changes increased with higher ME time expenditure during definition stage of product development because ME viewed these products as repeats and based decisions on prior designs without considering thoroughly the subtle differences[145]. • For the verification stage of product development, the result is the same for all products[146].

Table A-2: Summary of Coughlan's findings

---

[139] Coughlan: 1992, p.168.
[140] Coughlan: 1992, p.169.
[141] Coughlan: 1992, p.169.
[142] Coughlan: 1992, p.170
[143] Coughlan: 1992, p.168.
[144] Coughlan: 1992, p.169.
[145] Coughlan: 1992, pp.169-170.
[146] Coughlan: 1992, p.170.

Ettlie[147]

Background

Ettlie's study was done to fill a knowledge gap in concurrent engineering. The gap was the lack of details regarding how manufacturing personnel should be involved in the development of new products[148]. He focused on the nature of early manufacturing involvement (EMI) in development of new products; the term "early" refers to the concept development stage[149].

Hypotheses Tested or Questions Asked

Ettlie's paper explicitly stated three hypotheses[150] he wanted to test in order to highlight the role of manufacturing in new product development:

1. The fewer design change requests for a new product just before launch, the more likely the new product will be a commercial success.
2. Early (as opposed to late or no) manufacturing involvement (EMI) in the design process for new products in likely to reduce the number of pre-launch design change requests.
3. The more training provided for new product team members, the more likely EMI can and will be used in the development process.

Research Method

The study was based on two surveys targeted at two different samples of respondents. Each survey is described in turn.

The population of the first survey administered as part of Ettlie's study consisted of 122 US firms producing durable goods in the automotive, aerospace, machine tools, and appliance industries.[151]. The return rate was 36% (43 firms); the surveys were mostly filled out by mid-level managers within these firms[152].

---

[147] Ettlie, John E. "Early Manufacturing Involvement in New Product Development." Proceedings of the IEEE Engineering Management Conference, 1995. pp.104-109.
[148] Ettlie: 1995, p.104.
[149] Ettlie: 1995, p.104.
[150] Taken directly from Ettlie: 1995, pp.105-106.
[151] The surveyed population briefly described on p.104 and p.106.
[152] Ettlie: 1995, p.106.

The second survey[153] was sent to 431 US companies that performed R&D. It was to be filled out by chief technical officers or chief executive officers. Twenty-nine percent (126 firms) of these surveys were returned from firm that produce electrical machinery, instruments, transportation equipment, and non-electrical machinery.

All the findings below were derived from the two sets of survey responses.

Findings

The results from both surveys supported the three hypotheses the study set out to test[154]. Statistical analyses showed that return on investment was significantly associated with low number of design change requests before production started. Furthermore, early manufacturing involvement in new product development was significantly related to fewer design change requests before production start. Finally, data analyses showed that when more training is given to the design team, the more likely manufacturing would be involved early in new product development.

Fricke et al.[155]

Background

This paper differed from the majority of those reviewed, as exemplified by the paper by Hegde et al., in that it encompassed a larger variety of engineering changes, and explored the relationship between engineering changes and interactions among distinctive organizations. In fact, Fricke et al. stated that the term "changes", synonymous with engineering changes, "... encompasses all kinds of changes, whether changes of needs, requirements, specs, already built components, processes, cost, schedule and so on."[156] Furthermore, this paper explicitly categorized causes and effects, or impacts, of engineering changes.

Hypotheses Tested or Questions Asked

---

[153] The surveyed population briefly described on p.104 and p.106.

[154] The rest of the discussion about this paper come from pp.107-108.

[155] Fricke, Ernst, Bernd Gebhard, et al. "No Innovation Process without Changes, but..." *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. pp.601-608.

[156] Fricke et al.: 1997, p.601.

The study whose results are reported in the paper was descriptive. As such, the paper did not start out with a hypothesis to test. However, it focused on the following implicit questions:

1. What are the causes and effects of changes?
2. What are some strategies that can be used to exploit changes to facilitate innovation in designing systems?

Research Method

The authors and associated researchers held interviews with engineers and managers at about 20 firms in various German industries[157]. Interview results formed the basis of the descriptive study.

Findings

The findings answered the two implicit questions the authors sought to address. They included the causes and effects of changes in product development, and the strategies that can be used to manage and exploit the changes for product improvement.

The authors identified three broad categories of changes[158]: technical factors, human factors, and planning/management factors. Technical factors may cause engineering changes due to the possibility that in the development of complex systems (or products), adding a new technology or process can yield unexpected consequences that require engineering changes to address. Human factors can cause changes in design because people can be frequently forced to make decision based on incomplete information due to time pressures. The incompleteness of information may in turn be caused by delayed communications between people who have the updated information and those who need the updated information to make decisions. Finally, changes can be driven by planning/management factors such as poor coordination with one's external suppliers. Poor communication can also play into the planning and management across companies. Once a process was set up incorrectly due to the aforementioned problems, changes to the process or the resulting product might have to be made.

---

[157] Based on in-person discussion with Fricke, July 17, 1998.

[158] The discussion on findings regarding the causes of changes are based on Fricke et al.: 1997, p.602.

Fricke et al. identified both negative and positive effects[159] (or impacts) of engineering changes on product development. According to the authors, negative impacts are those associated with increased cost and delayed schedule. On the contrary, engineering changes can have positive impacts on product development because they represent opportunities to improve the product.

The existence of negative and positive impacts of engineering changes led the authors to proposed five strategies[160] for managing, and taking advantage of, engineering changes. The first method to manage changes is to have fewer of them. Fricke et al. suggested that a product development organization can reduce unnecessary changes while enabling innovation by thoroughly understanding the requirements, reducing unnecessary specifications, and distinguishing changes by their nature, timing, and likely effects. Second, changes can be better managed by detecting and making them as early as possible. The authors contended that necessary changes, when detected earlier in the product development process, can bring benefits to the product without risking cost and schedule problems. Furthermore, they suggested that early detection of changes can be enabled by incorporating end user input early in product development, and validating design concepts early using available software tools. The third way to manage engineering changes, according to Fricke et al., is to selectively implement only those that are necessary and useful. Fully estimating the effects of every such change would require a systems view. The estimation can also be facilitated by referring to similar engineering changes made in past product development efforts. Fourth, the authors proposed that engineering changes should be implemented to derive the maximum benefit with minimum resources. Effective communication can ensure that all relevant parties understand the requirements of the change, thereby implementing a change with the right resources at the right time. Finally, the authors proposed that product development organizations should learn from past engineering changes. This requires the product development organization to understand the causes and impacts of engineering changes it may wish to learn from.

---

[159] Discussion of effects of changes is based on pp.602-603 of the paper.
[160] Full-length discussion on the strategies can be found on pp.603-606 of the paper.

Kick[161]

Background

Kick's thesis was motivated by the need to better integrate diverse technical disciplines and people from different organizations into a complete system product[162]. The research was done as a 7-month internship for Leaders for Manufacturing program at MIT[163].

The thesis documented Kick's internship experience in establishing a single-document control process, and an expanded process to manage the system level configuration of an unprecedented product for the company at which he conducted the internship. It also contained a thorough discussion on the fundamentals of configuration management, and highlighted some interface issues across functional organizations. Another notable feature is that the thesis provided an enlightening discussion on differences between Class 1 and Class 2 engineering changes. Overall, the thesis was not about engineering changes themselves, but rather about structures to manage them during the development of a complex product.

Hypotheses Tested/Questions Asked

Two main research ideas were the focus[164]:

- Controlling design and documentation changes during product development
- System-level processes to integrate diverse technical disciplines.

Since the field-research experience focused on configuration management, the research areas were studied from the perspective of configuration management.

Research Method

The research method was Kick's internship itself, and the lessons learned were based on establishing two related configuration management processes, and review of appropriate literature[165]. The processes were established and implemented by Kick at a product development program at a private firm that was developing a new imaging system that was unprecedented for

---

[161] Kick, Mitchell Edward. *A System Level Configuration Control Process*. MIT Master of Science in Management and Master of Science Thesis. May 1993.
[162] Kick: 1993, pp.11-13.
[163] Kick: 1993, p.13.
[164] Taken directly from Kick: 1993, p.15.
[165] Kick: 1993, p.127.

the firm in terms of the product's market, high software content, nature and number of interfaces between technical components (hardware, software, and media), and high interdependency of functional organizations that must be integrated to develop the product[166].

Based on the two research areas and the research environment, the author established and implemented two configuration management processes[167]. The first was meant to control the Software Requirements Specification, the second was meant to manage the changes that would impact the entire system being designed.

Findings

The findings and lessons learned are based on literature review and on the experiences of one program at one company. Instead of describing the configuration management processes implemented by Kick, this section highlights the lessons learned regarding the integration of diverse technologies and functional organizations[168]. The lessons are summarized below.

- Technologies are different. People tend to specialize in certain fields. Consequently, they don't understand system-level issues.
- Lack of systems knowledge. Systems being developed contain advanced and interdependent technologies that it is difficult to understand all of them.
- Language barriers. Once again, a factor related to specialization of disciplines.
- Organizational behavior factors. Here Kick addressed the issue of the organization being entrenched in practices optimized for its previous products, and unable to modify its processes in time to accommodate the unprecedented imaging system.

It is precisely due to these difficulties, Kick argued, that system-level processes like the system-level configuration management process[169] he implemented can effect collaboration among the disparate technical disciplines and organizations through early and effective communications.

It is noted here that more discussion on experiences, successes, and problems of implementing integrative processes can be found in Hernandez[170] and Browning[171].

---

[166] Kick: 1993, pp.13-14.
[167] Kick: 1993, p.15.
[168] The discussions below are based on Chapter 6 of Kick's thesis.
[169] The development of that process was addressed in Chapter 4 of this thesis.

Hooper[172]

Background

Hooper's thesis reported on evaluation of the Boeing 777 electrical wiring system error corrective action process and his recommendations for improvements for the process. Making the Electrical Corrective Action Process (ECAP) more efficient was important because the more errors eliminated/corrected more quickly by design and electrical wiring personnel, the shorter the manufacturing cycle time of the aircraft would be; thus an improved process was important to Boeing's goal of raising production rate of the 777 aircraft in order to better adapt the delivery schedule to airlines' needs[173].

It is important to understand that Hooper's study focused on the process to solve errors in design and production of the 777's electrical wiring system, not on the design or planning process[174]. Furthermore, it is useful to note that design changes encountered by Hooper were categorized into four types[175]:

1. Errors that must be fixed. These errors precludes the completion of the electrician's work, or may lead to safety problems, and are always made known to designers.
2. Errors that need not be fixed. These can be worked around.
3. Design improvements.
4. Errors of clarity. These have to do with unclear instructions.

Overall, the study was based on one production sub-process of a product at a single company. It is a case study that contains rich details about its subject.

Hypotheses Tested/Questions Asked

---

[170] Hernandez, Christopher M. *Challenges and Benefits to the Implementation of Integrated Product Teams on Large Military Procurements*. MIT Master of Science in Management Thesis. June 1995.

[171] Browning, Tyson R. *Systematic IPT Integration in Lean Development Programs*. MIT Master of Science in Technology and Policy and Master of Science in Aeronautics and Astronautics Thesis. June 1996.

[172] Hooper, Eric Allen. *Improving the Boeing 777 Program's Corrective Action Process*. MIT Master of Science in Electrical Engineering and Master of Science in Management Thesis. May 1996.

[173] Hooper: 1996, pp.9-11.

[174] Hooper: 1996, p.11.

[175] For a full discussion on these types, see pp.33-37 of Hooper's thesis.

Based on the content of the thesis, the implicit research questions were[176]:

- Does the existing Boeing 777 Electrical Corrective Action Process (ECAP) meet the basic requirements of a corrective action process?
- What lessons from the 777 product development phase might be extracted and applied to improve the ECAP?

Research Method

Hooper's work was one case study based on the Boeing 777 Electrical Corrective Action Process. Production related data were collected by Hooper and included in the appendices of his thesis. It was a 7-month effort during which he spent two months shadowing a line manager.

Findings

Hooper outlined four major findings regarding his research subject, and they are summarized here[177] per Hooper's wording:

1. Inter-functional collaboration and communications led to the success of the 777 Program's design phase; they can lead to the success of the sustaining production phase as well.
2. An effective corrective action process resolves errors quickly, enables the communication of all errors, and enables the participating organizations to learn from their mistakes. In so doing, it enables the inter-functional collaboration and communication that allow the participants to improve the process that tie them together.
3. The ECAP as it exists today does not satisfy all the requirements of a corrective action process.
4. The ECAP's performance can be improved through an approach similar to the one used from the beginning of the program's design phase: philosophical changes can lead to structural changes which can in turn lead to behavioral changes.

Five major impacts of wiring errors were also noted by Hooper[178]:

---

[176] The questions were mainly derived from Section 1.2 of Hooper's thesis: a discussion on his project's goals and assumption.

[177] Detailed version of the findings are included in Chapter 8 of Hooper's thesis.

[178] Details shown in Chapter 3, pp.27-32.

1. Increased production and design cost. He described it as many people from many disciplines would have to spend time apart from other duties to deal with errors.
2. Increased support and administrative costs. These have to do with personnel dedicated to dealing with the errors.
3. Variable process flows and assembly times. Production may deviate from plan due to the fact that personnel having to take time to correct the errors.
4. Reduced product consistency. Different electricians may work around similar errors using different methods, so products are not exactly the same.
5. Low employee morale. Since cycle time reduction was high priority, employees felt the pressure to react to errors by coming up with work-arounds to fix design problems, instead of producing aircraft.

An additional item, although not noted in Hooper's thesis as one of the findings, is nevertheless a valuable lesson learned from his research. It has to do with the limits of computer-aided design (CAD) tools like Boeing's CATIA as used at the company at the time of Hooper's research. Hooper noted in Section 2.3 of his thesis that one cannot assume the ability to anticipate all production problems simply because a computer tool has simulation capability. In terms of the wire bundles he studied, many production errors were due to wire lengths not having accounted for bends and bulges that CATIA could not capture since CATIA modeled a wire bundle as a rigid tube. In this case, the CAD tool created the need to make design changes while at the same time prevented many others. Nevertheless, Hooper's discussion of this limitation highlighted the necessity to explicitly understand the simulation tools.

Wright[179]

Background

The intent of Wright's paper was to provide a survey of documented research on engineering changes. Wright defined an engineering change as "...a modification to a component of

---

[179] Wright, I. C. "A review of research into engineering change management: implications for product design." *Design Studies*, Vol.18, 1997. pp.33-42.

a product, after that product has entered production."[180] At the end of Wright's paper, the directions suggested for future engineering change-related studies helped shape the research documented in this thesis.

Hypotheses Tested/Questions Asked

The content of Wright's paper provided insight into the questions the author wanted to answer. Wright has provided views on:

- What directions and emphases had research in engineering changes adopted since 1980?
- Can any trend be established based on the findings of these efforts?
- What gaps of knowledge can be identified based on these findings?

Research Method[181]

Fifty-eight papers related to engineering changes from the 1980-1995 period were selected from 200 abstracts and read in full by Wright. The paper discussed 15 of the 58 papers, plus eight others. There was no indication as to why these papers were specifically chosen to be highlighted.

In addition, Wright also reviewed the funded research in UK that had to do with engineering changes. The data in this regard came from the Engineering and Physical Sciences Research Council (EPSRC).

Findings

Wright was able to classify the papers according to their emphases: 1) use of computer-aided design tools to minimize the need for engineering changes, and modify documents that are impacted by engineering changes; and 2) engineering change management methods[182]. The author observed papers in the first category tended to be product specific, while those in the latter category tended to be more general[183].

---

[180] Wright: 1997, p.33.
[181] Summarized from Wright: 1997, p.34.
[182] Wright: 1997, p.40.
[183] Wright: 1997, p.34.

Other observations were also noteworthy. First, Wright acknowledged having been unable to find engineering change studies based on business processes perspective[184]. Consistent with the first observation, Wright also noted that engineering change research have been done from the manufacturing perspective, and perhaps future engineering change research should study how changes can be the tool for product improvement[185].

Author Wright named several engineering change (EC)-related areas that were thought to be lacking in research[186]:

1. How do the reasons for, and purposes of, EC vary in different industrial environments?
2. Can companies take market effectiveness into account when assessing the benefits of proposed EC? What appropriate metrics can be determined to assess these criteria?
3. How can the marketing and design functions estimate the downstream costs of a proposed EC, rather than leaving this assessment to an EC management committee?
4. Is there a correlation between the number or type of engineering changes processed by company and the market competitiveness of its products?
5. What are the characteristics of activities and communication channels in an effective EC management control system?
6. To what extent does EC effectiveness influence design performance?
7. What does an EC process map look like from the marketing and design function point of view?
8. How does this map vary from that perceived from the manufacturing, production and inventory viewpoints, and how might these variations be accommodated?
9. What are effective and efficient EC processes, and can these be defined on type and generic bases?

What must be considered when using literature review results and trends such as those provided by Wright? It is important to bear in mind that 10 of the 23 highlighted works came

---

[184] Wright: 1997, p.40.
[185] Wright: 1997, p.42.
[186] Taken from Wright: 1997, pp.41-42.

from production- and inventory-related sources[187]. Therefore, it is reasonable to expect these papers to address issues of concern to the production and inventory communities, as opposed to the product development community. It is not clear then, whether the dominance is due to Wright's biases in selecting the papers to review, or the fact that much of engineering change-related work was done by the production and inventory communities. Combining the findings of Wright and the other works reviewed for this present research, it is reasonable to place more credibility onto the second possibility: many engineering change -related studies have been conducted from the manufacturing perspective addressing the design-manufacturing interface.

---

[187] The sources included *Production and Inventory Management* and conference proceedings of the American Production and Inventory Control Society.

This page is intentionally left blank.

Appendix B. Existing Frameworks for Categorizing Causes of Engineering Changes

This appendix documents the review of four frameworks with which causes of engineering changes have been previously studied in the literature and in practice. They are reviewed using the three criteria stated in Section 2.5: examine various product development issues, provide a systems view of US defense aerospace product development, and extract lessons learned.

Coughlan[188]

The company that supported Coughlan's research has been categorizing reasons for manufacturability-related engineering changes using the framework shown in Table B-1. It is unfortunate that each reason was not defined in Coughlan's publication.

Motivation for Manufacturability-related Engineering Changes	
1	Cost reduction
2	Material Substitution
3	Design Correction
4	Design improvement
5	Documentation change
6	New feature
7	Yield improvement

Table B-1: Reasons for manufacturability-related engineering changes documented in Coughlan's work

Examine a Variety of Product Development Issues

As Coughlan has indicated[189], the categories have been used by the divisions in the company to study manufacturing-related engineering changes. The contribution of product

---

[188] Coughlan, Paul D. "Engineering Change and Manufacturing Engineering Deployment in New Product Development" *Integrating Design and Manufacturing for Competitive Advantage.* Gerald Susman, Ed. New York, NY: Oxford University Press, 1992. pp.157-177.

[189] Coughlan: 1992, p.165.

development to the need for the changes might have been addressed by "Design correction", "Design improvement", and "Document change".

On the other hand, the framework discussed in Coughlan's paper and shown in Table B-1 does not explicitly study product development in detail. For example, it is impossible to determine whether a "Design correction" engineering change was related requirements definition, or any other process. For another example, should the company be interested in understanding how marketing may influence the design changes by forcing the incorporation of any "New feature," it is unlikely to determine the magnitude of this influence.

The remaining categories in Table B-1 focus on manufacturing or the design-manufacturing interface. For example, "Yield improvement" and "Material Substitution" relate directly to manufacturing. It is unclear which aspect of cost "Cost reduction" addresses. Is it specifically the cost of production, or the life cycle cost of the product? Overall, the framework included in Coughlan's study retains a manufacturing focus.

Provide Systems View of US Defense Aerospace Product Development

Since it appears that the framework was meant to concentrate on the manufacturing and the design-manufacturing interface within divisions of a company, it may be adequate to bound the "system" to that one interface. Therefore, the framework in its present form appears unable to provide a systems view of defense aerospace product development simply because there are more organizations and cross-organizational interfaces than this framework can explicitly address.

Extract Lessons Learned

The purpose of Coughlan's research was to address the role of manufacturing engineers in reducing engineering changes[190]. Coughlan and the company at which he conducted research also examined the variation of man-hours manufacturing engineers spent on the development of new products as function of development phase. Lessons were then drawn from correlation of the data sets. Therefore, the framework as shown in Table B-1 was suitable for extracting certain lessons learned.

---

[190] Coughlan: 1992, pp.157-158.

Fricke et al.[191]

The framework for categorizing causes of engineering changes, according to Fricke et al., is highlighted below in Table B-2.

Causes	
1	**Technical factors**
	• New technologies • New materials • Failure of simulation to identify all effects of an change
2	**Human factors**
	• Imperfect decision-making ability in the face of technical complexity • Insufficient communication/coordination among people doing different tasks • Incentive structure inadvertently encourage late reporting of changes • Decision makers wanted the change (otherwise unnecessary)
3	**Planning/Management factors**
	• Insufficient planning related to coordination with external suppliers • Planned processes impossible to implement • Faulty process planning • Needed information unavailable when a process calls for it

Table B-2: Framework for categorizing causes of engineering changes by Fricke et al.[192]

Examine a Variety of Product Development Issues

This framework allows the consideration of a variety of issues relevant to both product development and manufacturing. In fact, the authors intended to "...understand the nature of changes over the whole life-cycle of a system."[193] Elements of each of the three causes listed in Table B-2 can be applicable to many life cycle phases of a system.

Provide Systems View of US Defense Aerospace Product Development

The framework in Table B-2 provides a systems view for development of complex products, and can potentially be suitable for studying causes of engineering changes in US defense aerospace product development. For example, sub-categories under both "Human factors" and "Planning/management factors" can be applied to interactions between individuals

---

[191] Fricke, Ernst & Bernd Gebhard, et al. "No Innovation Process without Changes, but..." *Proceedings of Seventh Annual International Symposium of the International Council on Systems Engineering Vol. 1.* Los Angeles, CA: August 3-7, 1997. pp.601-608.

[192] Bulleted items paraphrased from the paper.

[193] Fricke et al.: 1997, p.601.

and between organizations. Therefore, the framework allows the examination of interface issues as possible contributors of engineering changes.

Extract Lessons Learned

In common with the framework discussed by Coughlan, the three major causes of engineering changes Fricke et al. discussed can allow the extraction of lessons learned as long as other data are available. Fricke et al.'s framework has already implied that data other than the number of engineering changes due to each cause should be collected. For example, insights into communications among communities would be gained when studying "Human factors" as a possible cause of engineering changes because the category forces an investigation into whether there is in fact insufficient communication among parties.

DCMC's Categorization of Class I ECPs[194]

One of the duties of the Defense Contract Management Command (DCMC) is monitoring the progress of all Department of Defense contracts[195]. The DCMC has been studying Class I engineering changes according to the framework shown in Table B-3.

Reasons for Class I ECPs under DCMC framework	
1	**Design error ECPs**
	• Improve performance to meet requirements • Eliminate interface incompatibilities • Eliminate hazardous conditions • Correct obvious design errors
2	**Requirements ECPs**
	• Implement upgrades • Implement modifications • Implement other requests (changes requirements or specifications)
3	**Improvement ECPs**
	• Eliminate environmental hazards • Improve manufacturing or performance beyond requirements
4	**Other**
	• Add sources to control drawings • Update material requirements • Replace obsolete parts

Table B-3: DCMC framework for categorizing reasons for Class I ECPs[196]

Examine a Variety of Product Development Issues

Since the categorization has been designed to study Class I ECPs in a wide variety of Department of Defense (DoD) prime contracts, it accounts for activities that are done during all phases of design and production. For example, an ECP implemented to "improve performance to meet requirements" under "Design error ECPs" can arise during detail design, after a test, or after the system has entered field service. Furthermore, the need to "replace obsolete parts" under "Other" can arise during design or production. Therefore, this framework is not limited to manufacturing.

Provide Systems View of US Defense Aerospace Product Development

---

[194] Details referred to here can be found in *DCMC Metrics Guide Book, Fourth ed.* Ft. Belvoir, VA. Downloadable from World Wide Web as PDF file from http://www.dcmc.hq.dla.mil and follow the hot link "Metrics under the column "Regulations & Manuals".

[195] Based on interview with a DCMC representative. 14 April 1998.

[196] DCMC Metrics Guidebook, p.73.

Although the existing framework can be more than adequate for examining many prime contractors performing to thousands of DoD prime contracts, and consolidating all ECP data at one agency (the DCMC), it may be too high-level to examine the interfaces between parties within individual product development programs. For example, writing an ECP to respond to a request to change specifications places the ECP as a "Requirements ECP" as shown in Table B-3. According to observations made during data collection for this present research, it is possible that such a request is driven by the need to administratively prepare specifications for an upcoming milestone review, or the request can be driven by the fact that the approved design baseline of one program is impacted by baseline shifts of another program. Therefore, the DCMC framework does not show the interactions between the two programs, which might be driving the need to do a large number of ECPs on some programs.

Extract Lessons Learned

The DCMC framework appears to be adequate for the purpose of learning high-level lessons about a large number of DoD prime contracts by a single agency. However, since extracting lessons about the management of a small number of specific programs requires detailed knowledge about the programs, doing so may be beyond the scope of the DCMC framework

MIL-STD-480B Class I ECP Justification Codes[197]

These justification codes from MIL-STD-480B explain why a Class I ECP is beneficial to the government[198]. Each code and its definition are shown in Table B-4.

Class I ECP Justification Codes	
1	**Code A**
	- Records only
2	**Code B**
	- Elimination of incompatibility at the interface of key elements of the system
3	**Code C**
	- Correction of deficiency discovered during functional check-outs or installation
4	**Code D**
	- Correction of deficiency (when no other code applies)
5	**Code O**
	- Significant effectiveness change to operational or logistical support
6	**Code P**
	- Prevention of production stoppage or delay
7	**Code R**
	- Reduction of present cost for the customer
8	**Code S**
	- Correction of a hazardous deficiency
9	**Code V**
	- Life cycle cost reduction

Table B-4: MIL-STD-480B framework for categorizing necessity of Class I ECPs[199]

Examine a Variety of Product Development Issues

The framework provided by MIL-STD-480B allows the examination of defense aerospace product development issues. Based on the definitions of the codes themselves, the framework encompasses issues that arise over the life cycle of a system. It addresses everything from contracting to design deficiencies, and operation and support characteristics.

Provide Systems View of US Defense Aerospace Product Development

This framework provides a systems view of the product development and acquisition process, and the products themselves. For example, Code B is for ECPs that fix incompatibility between key subsystems. According the observations made while collecting data for this

---

[197] *MIL-STD-480B Configuration Control - Engineering Changes, Deviations and Waivers*. 15 July 1988. The newer MIL-STD-973 is similar to, and superseded 480B, but no copy of 973 was available. Section 5.1.3 of 480B defines each justification code.

[198] MIL-STD-480B: 1988, Section 5.1.3.

research, it is possible that these subsystems are managed by different program offices. Code B does not exclude this possibility.

Extract Lessons Learned

Similar to the DCMC framework reviewed previously, the ECP Justification Codes are mainly for monitoring a large number of items of interest, not for studying individual programs in detail. The application of the framework requires knowledge about the contract governing a program, not knowledge about the history and management practices used in the program.

---

[199] Paraphrasing is used in the table to ensure clarity. Exact language can be found in MIL-STD-480B, Section 5.1.3.

Appendix C. Interview Questions for Contractor and Program Office Personnel

Interview Questions for Contractor Personnel

Note: The term "Programs" is used to represent the three case study programs. In addition, the term "company" represents the contractor company at which the interview was conducted.

Product Development Process

1. Please describe the product development process with respect to program phases in the Programs.
2. Please describe the company's internal engineering change/configuration management process at the Programs. How does the process depend on the program phase?

Nature of the System

3. Name of the system__________
4. Date on which requirements definition work on the system began__________
5. For this system, what level of specifications does the customer control__________
6. Please list the suppliers (mainly first tier) for this system:

Technology of the System

7. Please describe the system's technology content, i.e., generation of the processors, version of programming language, etc.
8. Please list the major components of the system
9. Given available choices of technology, what were the factors that led to the chosen technology? In other words, who or what decided which choice to go with?
10. At any phase of the program to which the system belongs, have the requirements for the system been changed by the customer to accommodate a new technology?

Use of Integrated Product Team (IPT) Structure

Please note: These questions will be modified based on how the developmental efforts were organized at the company)

11. Was the IPT structure used to develop this system? Yes_____ No_____

12. At what phase of the program was the IPT structure used for this system__________

13. Did suppliers participate in the development effort for this system? Yes_____ No_____

    If Yes, please describe the nature of the their involvement and what type of personnel (engineers, managers, production personnel, etc.) from the suppliers participated.

14. Did the customer participate in the development efforts? Yes_____ No_____

    If Yes, please describe the nature of the their involvement and what type of personnel from the customer participated.

15. Did the company's production personnel participate in the development of this system?

    Yes_____ No_____

    If Yes, please describe the nature of the their involvement and what type of personnel from production participated.

16. Of the prime contractor, suppliers, and customer, which party makes the final technical decisions regarding a system? How does the authority change as program progresses?

Experiences with CAD/CAM as a Communications Tool

17. Was CAD/CAM the primary communications tool between the company's Programs and their suppliers? Yes_____ No_____

    How has the use affected the need to make engineering changes?

18. Was CAD/CAM the primary communications tool between the company's Programs and their customers? Yes_____ No_____

    How has the use affected the need to make engineering changes?

Interview Questions for Program Office Personnel

General Information

1. Name of Program:________________________
2. Personnel in program IPT:
3. Prime contractor(s) for this program:_________________
4. Subcontractor(s) for this program:______________________

5. Contracts over which the program has jurisdiction:

Phases and Budget

6. Product development phases and their beginning & end dates:

Contract number	Contract type	Contract content	Contract award date	Nominal closeout date	Actual closeout date	Original contract amount	Contract amount to date	Remarks

7. Description of types of decisions made during each phase:

Top-level Program Management

8. Phase during which the IPT structure was first used by the prime contractor for this program:__________

9. Which level of contractors does the SPO program IPT have jurisdiction over?_____ (1=both the prime contractors and all subcontractors, 2=prime contractors and 1st tier subcontractors only, 3=prime contractors only)

Technology Decisions

10. The program seeks to incorporate newest technology into the subsystems for which it is responsible_____ (Yes=1, No=0)

11. The program seeks to incorporate the most reliable (lowest risk in terms of cost, schedule, and performance), but not necessarily the most modern, technology into the systems for which it is responsible_____ (Yes=1, No=0)

Additional Details & Subsystems Listing

12. Background information about the program:

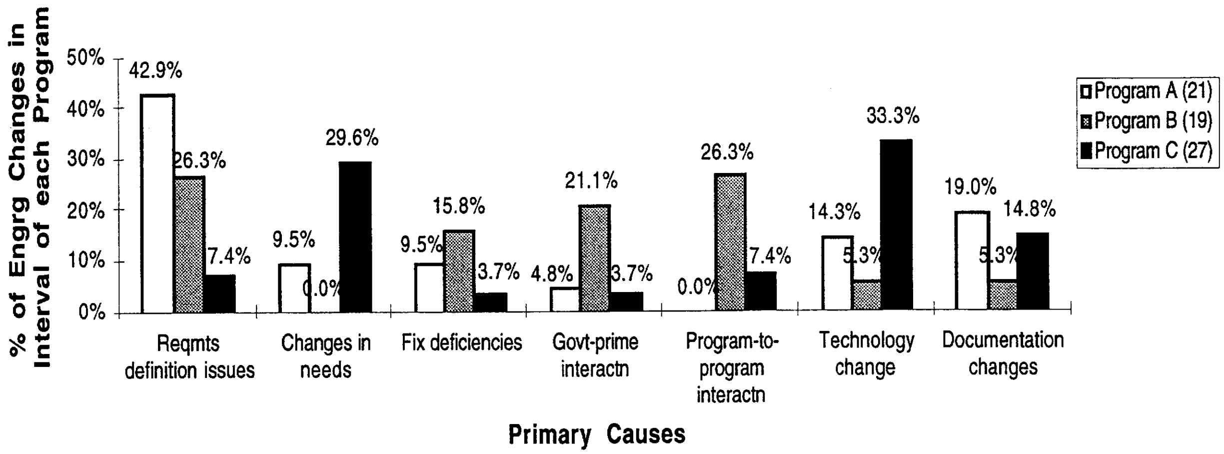
13. Systems for which this program is responsible (Reasons for technology choice: 1=lowest cost, 2=COTS, 3=most reliable, 4=newest technology, 5=best performance in terms of processing time, etc.) *Part of this question may not be appropriate for the project level*

System name	Spec number	Functionality	Technology content	3 major reasons for technology choice	Funds spend on system to date

This page is intentionally left blank.

Appendix D. Causes of Engineering Changes: Time-Based Data Normalization

The Appendix lists and briefly discusses the available results from normalization of engineering change data in Chapter 4 by using only the data with the first 3.5 years of available data from each program. As mentioned in Chapter 4, this approach had the shortcoming of ignoring the similarity of the programs in terms the phase they were in when this research began.

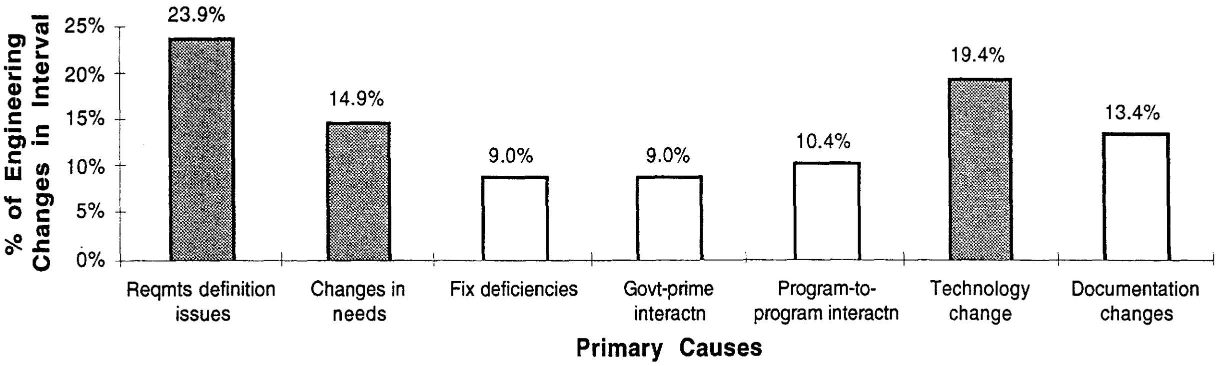


Based on a total of 67 engineering changes from the first 3.5 years of each of the three programs.

Figure D-1: Time-normalized primary causes of engineering changes

Some differences in the patterns of the data with and without this normalization are noted. When Figure D-1 above is compared to Figure 4-9, it is clear that many of Program A's engineering changes due primarily to the need to fix deficiencies happened late (beyond the first 3.5 years) in the program, and were thus excluded. Furthermore, the relative importance of the need to realign documentation as a primary cause of engineering changes in Program A seemed to have been increased by this normalization. Program A ECP descriptive data showed that there were many engineering changes that were done to simply realign documentation during the program's first 3.5 years. Such engineering changes were retained by the normalization. In addition, the normalization seems to also have diminished the importance of changes in technology as one of the dominant primary causes of engineering changes in Program B. An examination of the ECP descriptive data would indicate that technology-related engineering changes in Program B were implemented more recently. Thus, many of them were excluded by this normalization.

The aggregated results across the three program also show changes in needs to be one of the three dominant causes. The results are shown in Figure D-2.



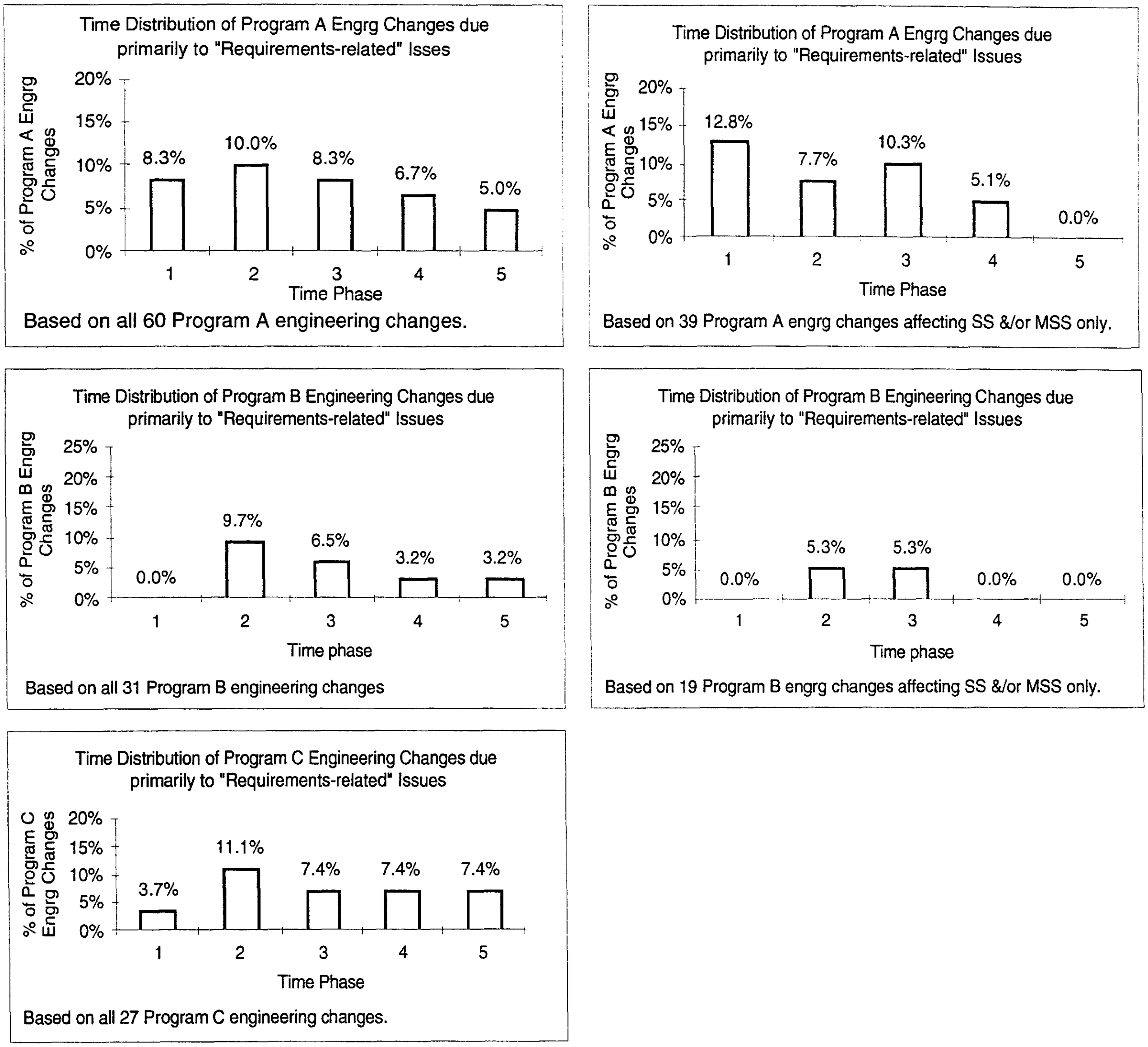
Based on a total of 67 engineering changes from the first 3.5 years of each of the three programs.

Figure D-2: Time-normalized dominant causes of engineering changes across the three programs

Appendix E. Primary Causes Over Time

This appendix shows the data for the analysis of the relationship between primary causes of engineering changes and time. Each cluster of plots represents each high-level cause of engineering changes discussed in Section 3.3. Data from each of the three case-study programs are represented in each row within each cluster of plots. The left-hand-side column shows data using all engineering changes in the three programs, while the right-hand-side column shows data based on engineering changes affecting only the system specification (SS) and/or mission system specification (MSS). It is useful to note that Program C engineering change data do not require specification-based normalization because they only pertain to system specification and/or mission system specification.

Requirements-Related Issues


Time Distribution of Program A Engrg Changes due primarily to "Requirements-related" Isses

Based on all 60 Program A engineering changes.

Time Distribution of Program A Engrg Changes due primarily to "Requirements-related" Issues

Based on 39 Program A engrg changes affecting SS &/or MSS only.

Time Distribution of Program B Engineering Changes due primarily to "Requirements-related" Issues

Based on all 31 Program B engineering changes

Time Distribution of Program B Engineering Changes due primarily to "Requirements-related" Issues

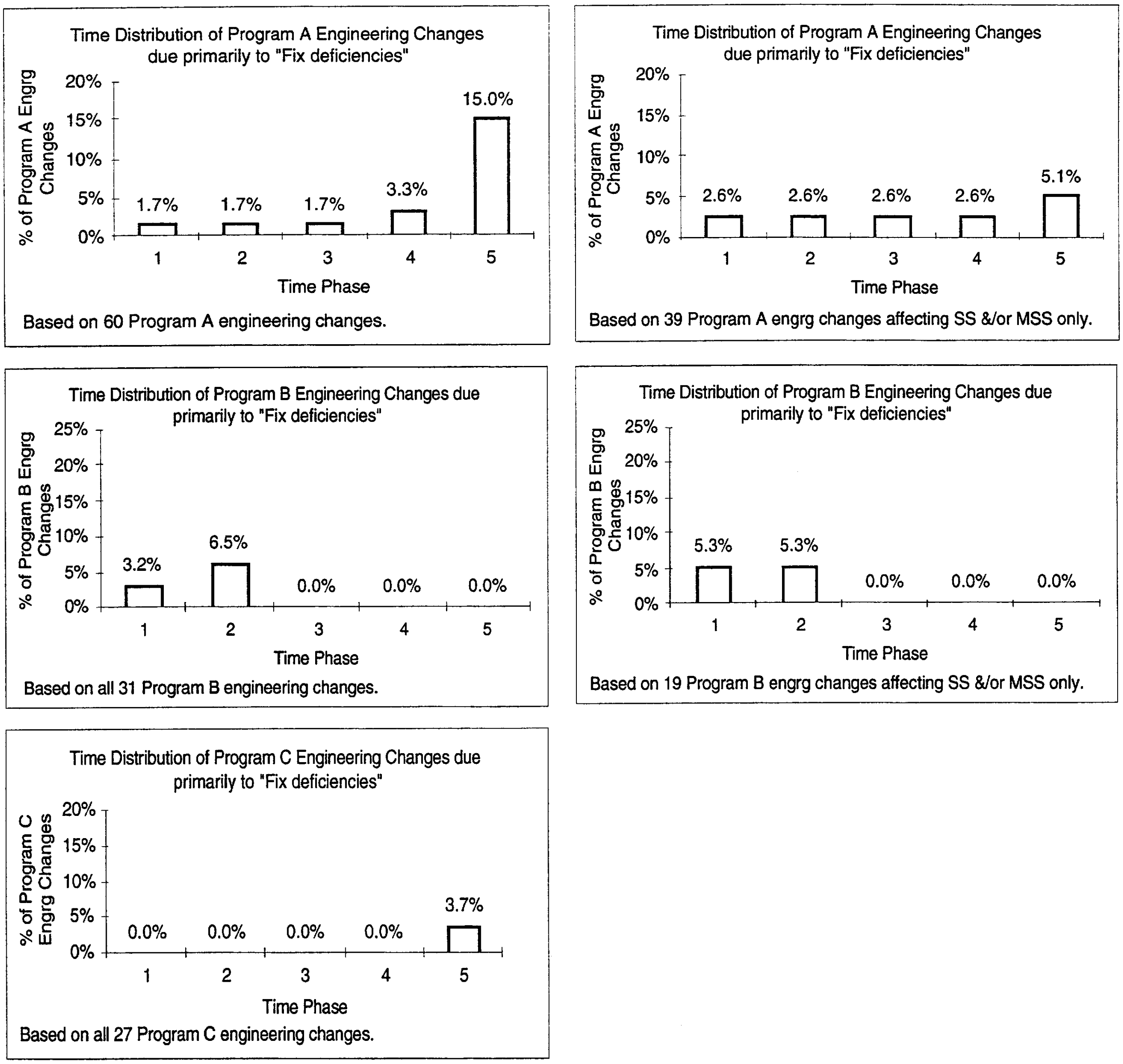
Based on 19 Program B engrg changes affecting SS &/or MSS only.

Time Distribution of Program C Engineering Changes due primarily to "Requirements-related" Issues

Based on all 27 Program C engineering changes.

Figure E-1: Time distribution of engineering changes due primarily to requirements-related issues

Fix Deficiencies


Time Distribution of Program A Engineering Changes due primarily to "Fix deficiencies"

Based on 60 Program A engineering changes.

Time Distribution of Program A Engineering Changes due primarily to "Fix deficiencies"

Based on 39 Program A engrg changes affecting SS &/or MSS only.

Time Distribution of Program B Engineering Changes due primarily to "Fix deficiencies"

Based on all 31 Program B engineering changes.

Time Distribution of Program B Engineering Changes due primarily to "Fix deficiencies"

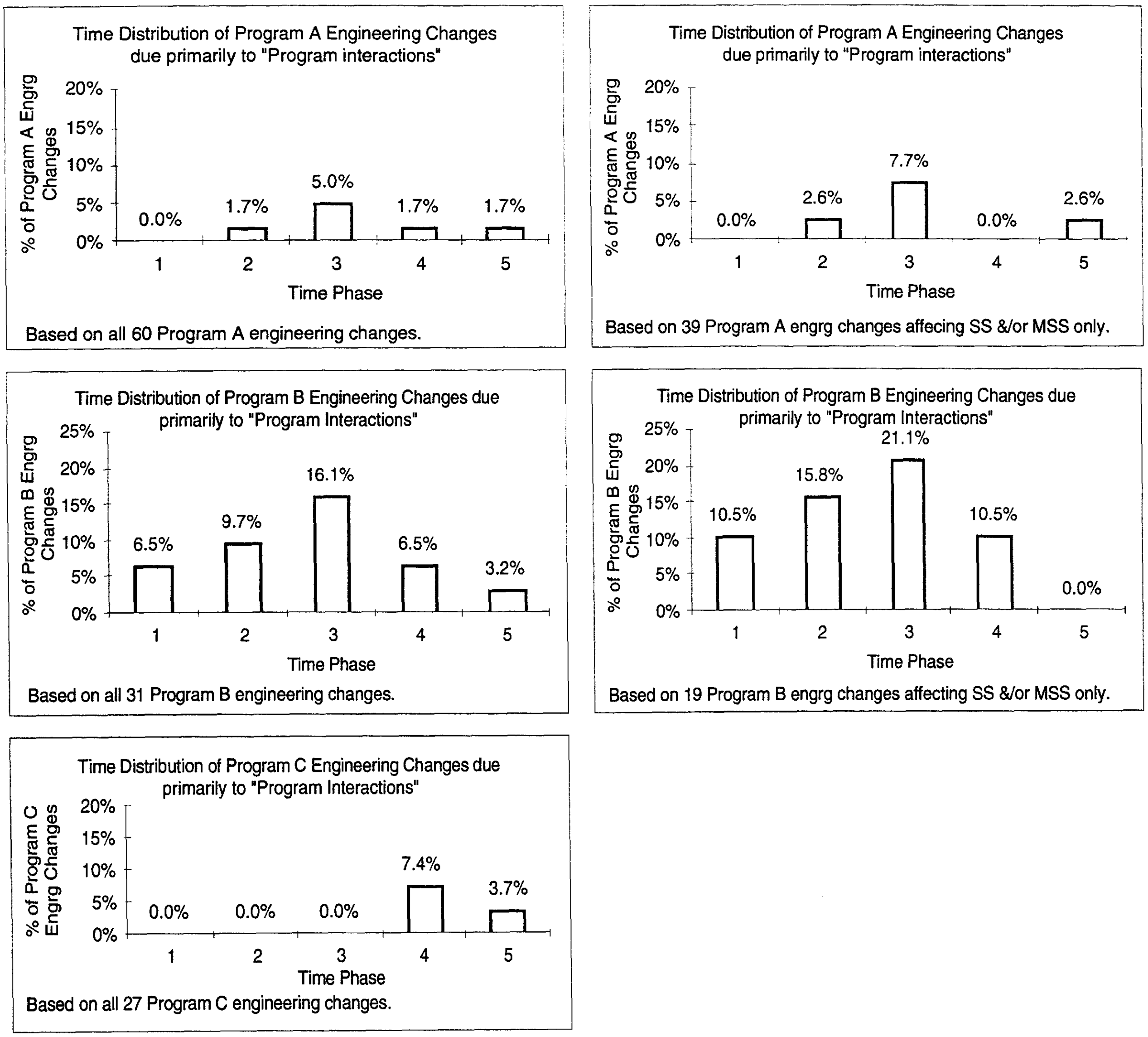
Based on 19 Program B engrg changes affecting SS &/or MSS only.

Time Distribution of Program C Engineering Changes due primarily to "Fix deficiencies"

Based on all 27 Program C engineering changes.

Figure E-2: Time distribution of engineering changes due primarily to fixing deficiencies

Program Interaction


Time Distribution of Program A Engineering Changes due primarily to "Program interactions"

Based on all 60 Program A engineering changes.

Time Distribution of Program A Engineering Changes due primarily to "Program interactions"

Based on 39 Program A engrg changes affecing SS &/or MSS only.

Time Distribution of Program B Engineering Changes due primarily to "Program Interactions"

Based on all 31 Program B engineering changes.

Time Distribution of Program B Engineering Changes due primarily to "Program Interactions"

Based on 19 Program B engrg changes affecting SS &/or MSS only.

Time Distribution of Program C Engineering Changes due primarily to "Program Interactions"

Based on all 27 Program C engineering changes.

Figure E-3: Time distribution of engineering changes due primarily to program interaction

Technological Changes

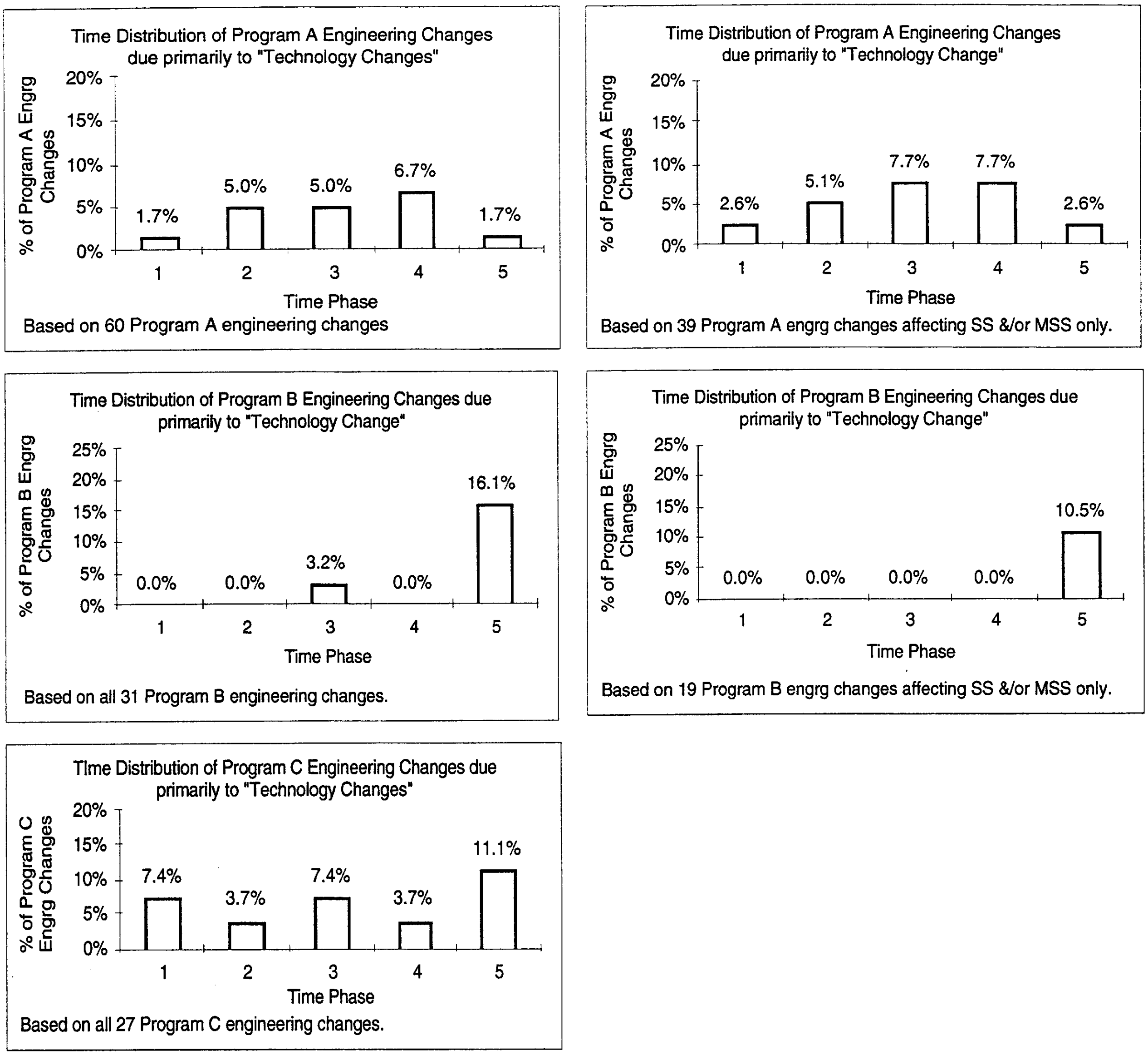
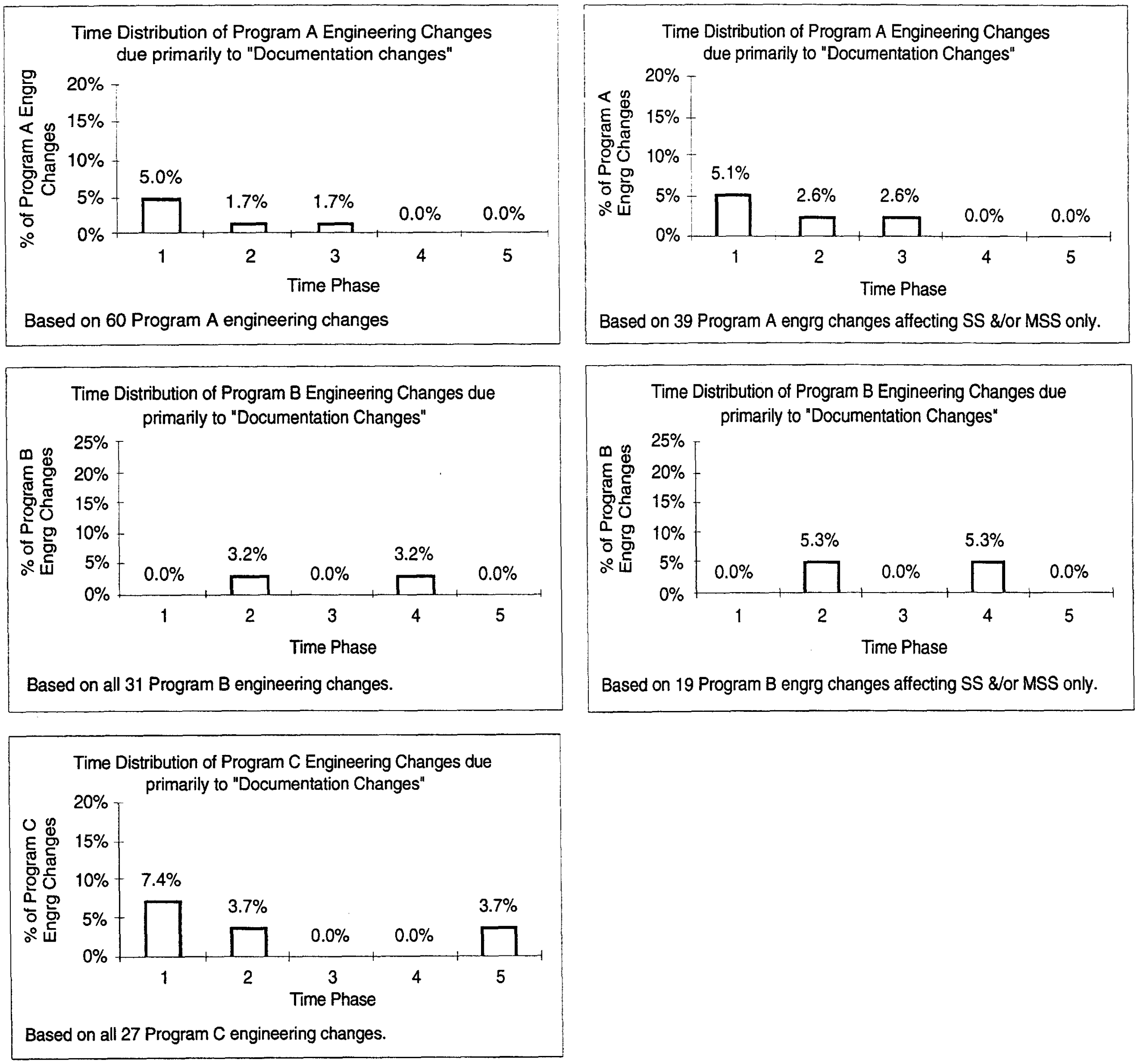


Figure E-4: Time distribution of engineering changes due primarily to technological changes

Documentation Changes



Time Distribution of Program A Engineering Changes due primarily to "Documentation changes"

Based on 60 Program A engineering changes

Time Distribution of Program A Engineering Changes due primarily to "Documentation Changes"

Based on 39 Program A engrg changes affecting SS &/or MSS only.

Time Distribution of Program B Engineering Changes due primarily to "Documentation Changes"

Based on all 31 Program B engineering changes.

Time Distribution of Program B Engineering Changes due primarily to "Documentation Changes"

Based on 19 Program B engrg changes affecting SS &/or MSS only.

Time Distribution of Program C Engineering Changes due primarily to "Documentation Changes"

Based on all 27 Program C engineering changes.

Figure E-5: Time distribution of engineering changes due primarily to documentation changes

Appendix F. Bibliography

This appendix lists the references that this research directly and indirectly benefited from. The sources listed in the first three sections were directly related to this research. Those listed in the last ("Miscellaneous") section were helpful in providing broader background information, and might be helpful for future research.

Background

Judd, Charles M., Eliot R. Smith, & Louise H. Kidder. *Research Methods in Social Relations, 6th ed*. Fort Worth, TX: Harcourt Brace Jovanovich College Publishers, 1991.

Rebentisch, Eric. 15.340J/16.451J/TPP43 Seminar in Social Science Research Methods. MIT course, Fall 1997.

Gansler, Jacques S. *Affording Defense*. Cambridge, MA: The MIT Press, 1991.

Barkan, Philip. "Productivity in the Process of Product Development - An Engineering Perspective". *Integrating Design and Manufacturing for Competitive Advantage*, Gerald Susman, Ed. New York, NY: Oxford University Press, 1992.

Hernandez, Christopher M. *Challenges and Benefits to the Implementation of Integrated Product Teams on Large Military Procurements*. MIT Master of Science in Management Thesis. June 1995.

Greg C. Manuel & Christopher M. Hernandez. "IPD Effectiveness/Engineering Change Research Project Proposal." Letter to Lean Aircraft Initiative consortium members. Reference Number R001-96-001. 23 April 1996.

Browning, Tyson R. *Systematic IPT Integration in Lean Development Programs*. MIT Master of Science in Technology and Policy and Master of Science in Aeronautics and Astronautics Thesis. June 1996.

McNutt, Ross T. *Reducing DoD Product Development Time: The Role of the Schedule Development Process*. MIT Doctoral Dissertation. December 1998.

Systems Concepts

Goode, Harry H. & Robert E. Machol. *System Engineering: An Introduction to the Design of Large-Scale Systems*. New York, NY: McGraw-Hill Book Company, Inc., 1957.

Ellis, David O. & Fred J. Ludwig. *Systems Philosophy.* Englewood Cliffs, NJ: Prentice Hall, Inc., 1962.

Flood, Robert L. & Ewart R. Carson. *Dealing with Complexity: An Introduction to the Theory and Application of Systems Science, 2nd ed.* New York, NY: Plenum Press, 1993.

Boppe, Charles W. 16.870 Aerospace Product Design. MIT course, Fall 1996.

Warmkessel, Joyce. "Requirements Generation and Specification". Planned material for MIT course. 1998.

Systems Engineering, Configuration Management, and Engineering Changes

Beam, Walter R. *Systems Engineering: Architecture and Design.* New York, NY: McGraw-Hill Publishing Company, 1990.

Blanchard, Benjamin S. *System Engineering Management.* New York, NY: John Wiley & Sons, Inc., 1991.

Grady, Jeffrey O. *System Requirements Analysis.* New York, NY: McGraw-Hill, Inc., 1993.

Samaras, Thomas T. & Frank L. Czerwinski. *Fundamentals of Configuration Management.* New York, NY: Wiley-Interscience., 1971.

MIL-STD-480B Configuration Control - Engineering Changes, Deviations and Waivers. 15 July 1988.

Balcerak, K. J. & B. G. Dale. "Engineering change administration: the key issues". *Computer-Integrated Manufacturing Systems, Vol. 5, No. 2,* 1992. pp.125-132.

Coughlan, Paul D. "Engineering Change and Manufacturing Engineering Deployment in New Product Development". *Integrating Design and Manufacturing for Competitive Advantage,* Gerald Susman, Ed. New York, NY: Oxford University Press, 1992.

Hegde, G. G., Sham Kekre, and Sunder Kekre. "Engineering changes and time delays: A feled investigation". *International Journal of Production Economics, Vol. 28,* Elsevier Science Publishers B.V., 1992. pp.341-352.

Kick, Mitchell Edward. *A System Level Configuration Control Process.* MIT Master of Science in Management Thesis. May 1993.

Pittman, R. Bruce. "Accommodating Change: The Dynamic System Engineering Process". *Proceedings of the Third Annual International Symposium of National Council on Systems Engineering.* 1993. pp.63-72.

Ettlie, John E. "Early Manufacturing Involvement in New Product Development". *Proceeding of the IEEE Engineering Management Conference*, 1995. pp.104-109.

Monahan, Ray E. *Engineering Documentation Control Practices and Procedures.* New York, NY: Marcel Dekker, Inc., 1995.

DCMC Metrics Guide Book, 4th ed. Ft. Belvoir, VA. Downloadable from the World Wide Web as PDF file from http://www.dcmc.hq.dla.mil, and follow the hotlink "Metrics" under the column "Regulations & Manuals".

Hooper, Eric Allen. *Improving the Boeing 777 Program's Corrective Action Process.* MIT Master of Science in Electrical Engineering and Master of Science in Management Thesis. May 1996.

Fricke, Ernst, Bernd Gebhard, et al. "No Innovation without Changes, but..." *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. pp.601-608.

Wright, I. C. "A review of research into engineering change management: implications for product design". *Design Studies, Vol. 18*, 1997. pp.33-42.

Miscellaneous

Ramachandran, Natarajan, Noshir A. Langrana, et al. "Initial Design Strategies for Iterative Design". *Research in Engineering Design, Vol. 4*, 1992.

Bellagamba, Laurence. "Using Control Charts to Measure Systems Engineering Effectiveness". *Proceedings of the Fourth Annual International Symposium of National Council on Systems Engineering, Vol. 1.* August 10-12, 1994, San Jose, CA. pp.815-821.

Oliver, David W. "A Life Cycle for Commercial and Aerospace Systems Discovery". *Proceedings of the Fourth Annual International Symposium of National Council on Systems Engineering, Vol. 1.* August 10-12, 1994, San Jose, CA. pp.733-738.

Alford, Mack. "Issue Driven Design: Planning and Managing Design Iterations". *Proceedings of the Fourth Annual International Symposium of National Council on Systems Engineering, Vol. 1.* August 10-12, 1994, San Jose, CA. pp.509-516.

Safoutin, Michael J. "The Iterative Component of Design". *Proceedings of the IEEE International Engineering Management Conference*, 1996. pp.564-569.

Harrison, Kunle & Clement C. Wilson. "Evaluating Configuration Complexity in Machines". *Journal of Engineering Design, Vol. 8, No. 2*, Abingdon Oxfordshire, UK, 1997.

Bahill, Terry A. & Frank F. Dean. "The Requirements Discovery Process". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1*. August 3-7, 1997, Los Angeles, CA. pp.261-268.

Bruno, Michelle & Brian W. Mar. "Implementation of the Systems Engineering Discipline". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1*. August 3-7, 1997, Los Angeles, CA. pp.253-259.

Buede, Dennis M. & Steven Charbonneau. "Considerations in Developing Originating Requirements". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1*. August 3-7, 1997, Los Angeles, CA. pp.285-292.

Gordy, Lowell W., Jr. "Process Change in Systems Engineering: From Document-Driven to Model-Based Approach". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1*. August 3-7, 1997, Los Angeles, CA. pp.847-853.

Jackson, Scott. "Systems Engineering for Commercial Aircraft". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1*. August 3-7, 1997, Los Angeles, CA. pp.63-70.

Kollmorgen, Leland S. & William S. Terry. "Joint Development Teams in Action: Government and Industry Perspectives". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1*. August 3-7, 1997, Los Angeles, CA. pp.679-685.

Lake, Jerome G. "Thoughts About Life Cycle Phases: How a System is Developed Incrementally". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1*. August 3-7, 1997, Los Angeles, CA. pp.493-499.

Laporte, Claude U. & Nicola R. Papiccio. "Development and Integration of Engineering Process at Oerlikon Aerospace". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1*. August 3-7, 1997, Los Angeles, CA. pp.633-640.

Mar, Brian W. "Back to Basics Again--A Scientific Definition of Systems Engineering". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1*. August 3-7, 1997, Los Angeles, CA. pp.229-236.

Martin, James N. "A Process for Requirements and Architecture Definition". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. pp.381-388.

Meilich, Abe. "Lessons Learned from Use of a Computer-based Requirements Management Tool in the Project Configuration Control Board Environment". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. pp.705-712.

Roe, Charles L. "System Integration and Test in Integrated Product and Process Development (IPPD): Engineering Out the Surprises". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. pp.671-678.

Thomas, L. Dale. "A Quantitative Metric of System Development Complexity". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. pp.205-212.

Thornton, John A. & Michael A. Luczak. "An Approach to Successful Integrated Product and Process Development (IPPD)". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. pp.663-670.

Wenzel, Stefan, Thomas Bauch, et al. "Concurrent Engineering and more...A Systematic Approach to Successful Product Development". *Proceedings of the Seventh Annual International Symposium of the International Council on Systems Engineering, Vol. 1.* August 3-7, 1997, Los Angeles, CA. pp.617-624.

"New Attack Submarine: More Knowledge Needed to Understand Impact of Design Changes". United States General Accounting Office Report. April 1998.

This page is intentionally left blank.

D120 - 15